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Krishna Naudin

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Cropping system design and trade-offs around biomass use for Conservation Agriculture in Cameroon and Madagascar

Krishna Naudin

Thesis committee

Promotor
Prof. dr. K.E. Giller
Professor of Plant Production Systems
Wageningen University

Co-promotor
Dr. E. Scopel
Research Scientist
Centre de coopération Internationale en Recherche Agronomique pour le Développement (CIRAD)
Antananarivo, Madagascar

Other members
Prof. dr. P. Tittonell, Wageningen University
Dr. M. Wopereis, AfricaRice, Cotonou, Benin
Dr. M. Pulleman, Wageningen University
Dr.ir. J. Vos, Wageningen University

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Krishna Naudin
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Conservation agriculture is defined by three main principles: minimum soil disturbance, permanent soil cover and crop rotations. CA is promoted as a promising technology for Africa, but to date, only a small area under CA fully complies with the above three principles. CA has both short and long term effects on crop productivity and sustainability through the modification of various agroecological functions. These functions are related to the quantity of crop and cover crop biomass produced and kept as mulch. One of the main challenges in designing CA for smallholder farming systems in developing countries is the competing uses for biomass, in particular for feeding livestock. The main difficulties are linking the efficiency of agroecological functions to varying degrees of biomass export, and evaluating the performance of cropping systems at farm level, which is where the decisions are made. In North Cameroon the quantity of biomass produced in the field has been doubled by associating a cover crop with a cereal crop. Part of the biomass was consumed by cattle during the dry season but the quantity of mulch that remained on the ground had a positive impact on the cotton water balance in the driest part of North Cameroon. In the Lake Alaotra region of Madagascar, the soil cover in rice fields under CA can vary, from 30% to 84% even in the same type of field depending on the plant used as cover crop, the quantity of biomass produced and management of the residues. The range is even greater when different kinds of fields are taken into consideration. Of course, the different agroecological functions can be fulfilled to a greater or lesser extent depending on the amount of available biomass and the resulting soil cover. The relationship between the quantity of biomass and soil cover has been calculated for different kinds of residues. We used these relationships to explore the variability of soil cover that could be generated in farmers' fields, and to estimate how much of the biomass could be removed to feed livestock while leaving sufficient soil cover. Our results showed that under farmers' conditions in Madagascar, the production and conservation of biomass was not always sufficient to fulfill all the agroecological functions of mulch. For example, partial export of biomass to be used as forage might have no effect in terms of erosion control but may considerably reduce the efficiency of physical weed control. As the balance between the potential benefits of exporting biomass and the efficiency of agroecological functions varies depending on the constraints and goals of each farm, we chose to analyze the potential benefits of exporting aboveground biomass to feed cattle at farm level. To this end, we modeled different size farms in Madagascar to investigate the relation between raising dairy cows and efficient application of CA. Our aim was to explore trade-offs and synergies between combinations of CA practices (i.e. different amounts of biomass exported) and the size of dairy cow herds (varying biomass needs and animal production). Changing the percentage of soil cover in CA plots did not significantly modify total farm net income, as this was more influenced by the characteristics of the milk market. Overall, CA systems can be beneficial for dairy cow farmers thanks to the forage produced, although the milk market and thus the value of biomass for forage, has a major influence on the way CA can be implemented at field level. To explore the range of possible cropping systems in a given biophysical situation, we created a tool named PRACT (Prototyping rotation and association with cover crop and no till). We used this tool to organize expert knowledge on crops and cover crops, biophysical characteristics of fields and agronomic rules and to link them using Malagasy conditions. PRACT generate a list of cropping systems, i.e. crops and cover crops and their sequences over three years. These cropping systems are characterized by their potential agroecological functions and crop production. The cropping systems are first selected based on the biophysical requirements of plants, plant compatibility and agronomic rules. But all the systems are not suitable for every kind of farm. Consequently using PRACT outputs, a second selection of cropping systems can be made based on the characteristics of the cropping system, i.e. crop production and agroecological functions. In this way, the selected cropping systems can be reduced to a number that can reasonably be handled by technicians and farmers. Finally, we recommend a more rigorous definition and characterization of treatments when comparing CA to conventional systems to obtain a clearer view of the link between the impact of CA, crop rotations and the level of biomass production.

Key words: conservation agriculture, cropping system design, optimization, cover crops, cotton, rice, Cameroon, Madagascar

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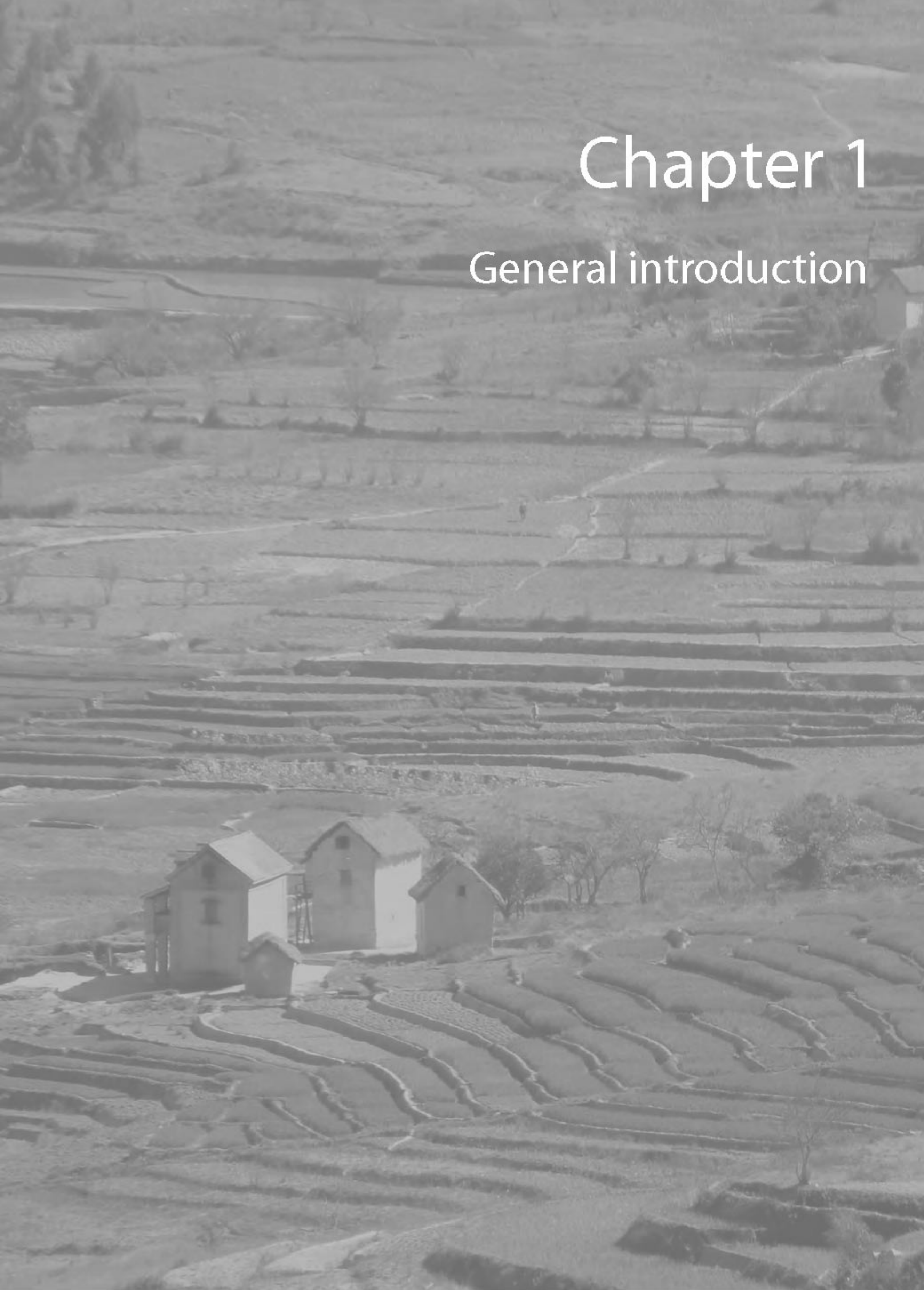
Chapter 1

General introduction



Chapter 1

General introduction

1.1 Conservation agriculture

Policy makers, scientists, and civil society agree that the increases in crop and animal production that are needed to feed the world's growing population have to be more sustainable than was the case during the previous "Green Revolution" (Sanchez et al., 2009; Snapp et al., 2010). Among the solutions put forward, ecological intensification (Doré et al., 2011), or agroecology, is increasingly considered to be the best way the tackle the issue of sustainable production (Wezel and Soldat, 2009; Schutter, 2010). Among agroecology systems, conservation agriculture (CA) is promoted as a promising technology for Africa (Fowler and Rockstrom, 2001; Hobbs, 2007; Hobbs et al., 2008). CA is defined by three principles (FAO, 2012a): (i) direct seeding; (ii) permanent organic soil cover; (iii) diversification of crop species grown in sequence and/or in association. When each of the functions and impacts of CA are considered individually (Fig. 1.1), they appear to be very promising in most agricultural situations but to date there have been few successful CA systems in smallholder agriculture in sub-Saharan Africa. Successful dissemination and adoption of a new technology is the result of complex interactions between the partners and the socio-economic context concerned. However, the first step is to identify appropriate technologies to propose to farmers. The research reported here focused on understanding what can be improved in the design of CA cropping systems for smallholders in developing countries. We based our analysis on two locations in Africa, North Cameroon and Madagascar, and combined experiences, data collected in farmers' fields, and modelling.

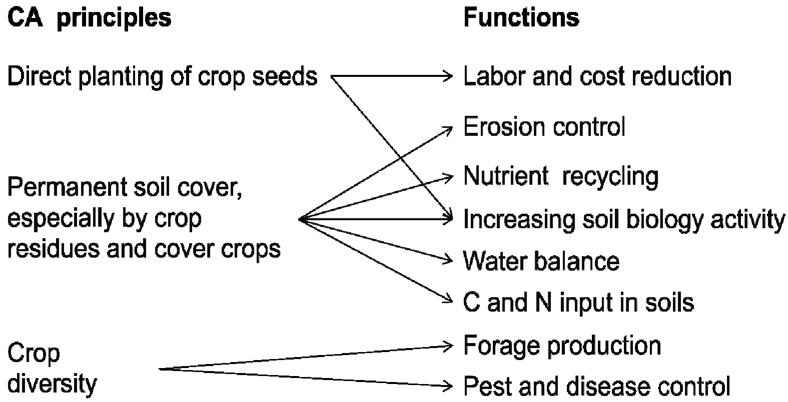


Figure 1.1. The relationships between the underlying CA principles and expected beneficial functions adapted from FAO (2012a), Hobbs, (2007) and Lal (2008).

A closer look at the three principles of CA (Fig. 1.1) shows that the majority of studies focus on the first principle, i.e. direct planting, without explicitly referring to soil cover and crop sequence and association. This is perhaps one the main reasons for the confusion in the names used to describe different agricultural practices, as conservation agriculture has often been confused with zero till (ZT) (Fuentes et al., 2010), no till (NT) (Yirenkyi, 2002; Bayer et al., 2006), conservation farming (CF) (Rockström et al., 2009) and conservation tillage (CT) (Mupangwa et al., 2008). Together with the use of herbicides, direct seeding was the key to the development of zero tillage and CA systems in Brazil, which is not the case for smallholder farms in developing countries in general, and sub-Saharan Africa in particular. As most smallholder farmers in sub-Saharan Africa do not have access to implements such as conventional seeding equipment, changing equipment it is not a major challenge for them. In most cases, they farm small areas and sow crops by hand without mulch formed of crop residues. Sometimes they plant using a digging stick. The biggest problems faced by smallholder farmers in sub-Saharan Africa when they want to use CA are related to the second and third principles, i.e. permanent soil cover and crop diversification. Permanent soil cover is difficult to achieve as there are competing uses for plant biomass, particularly as feed for livestock (Giller et al., 2009). This is one of the major concerns about the suitability of CA in sub-Saharan Africa along with other limitations such as the knowledge-intensive nature of CA systems, the need for particular equipment or pesticides, land tenure, and the contrasting results of studies of its agronomic and socio-economic impacts (Giller et al., 2011; Andersson and Giller, 2012). In addition to leave mulch on the field, it is also difficult to introduce or change crop rotations, and to introduce new crops and cover crops, as these farmers have limited resources. Thus, in this work, I focused on these aspects of cropping system design.

Among the 48 papers we identified in refereed scientific journals that compared CA and conventional cropping systems around the world, only ten provided data on the amounts of above-ground biomass produced by main crops and cover crops, three provided data on the percentage of soil cover, and only one provided data on both (Table 1.1).

Table 1.1 Quantitative characterization of mulch (biomass and soil cover) in 48 studies comparing CA and conventional techniques

Biomass data	**Soil cover data**	**References**
No	No	Schillinger, Holland, 2003; Lal, 2004; Govaerts et al., 2006a, 2007cad; b, 2008, 2009b; a; Gupta and Seth, 2007; Kosgei et al., 2007; Knowler and Bradshaw, 2007; Hobbs, 2007; Chivenge et al., 2007; Munoz et al., 2007; Brevault et al., 2007; Gowing and Palmer, 2008; Erenstein et al., 2008; Lichter et al., 2008; Hobbs et al., 2008; Erenstein and Laxmi, 2008; Céline et al., 2009; Doane et al., 2009; Gebreegziabher et al., 2009; Mazvimavi and Twomlow, 2009; Jat et al., 2009; Liang, 2010; Fuentes et al., 2010; Jan et al., 2010; Prosperi et al., 2011; Marongwe et al., 2011; Carbonell-bojollo et al., 2011; Rusinamhodzi et al., 2011; Farooq et al., 2011
Yes	No	Limon-Ortega et al., 2006; Mupangwa et al., 2007; Makurira et al., 2007; Metay et al., 2007; Chatskikh et al., 2009; Affholder et al., 2010; Naudin et al., 2010; Murungu et al., 2011; Dalal et al., 2011
No	Yes	Ribeiro et al., 2011; Rodríguez-Lizana et al., 2008
Yes	Yes	Boulal and Gómez-Macpherson, 2010

Surprisingly few studies quantify the amount of available mulch and the percentage soil cover even though much of measured and expected performance of CA is directly influenced by these variables.

This research was conducted in two developing countries; Cameroon and Madagascar. Before describing the objectives and outline of the thesis (1.3) I describe the context within which the work took place.

1.2. Context

1.2.1 North Cameroon

The North and the Far North Provinces of Cameroon have heterogeneous rainfall (600 to 1400 mm) (Fig. 1.2), relief (vast plains and steep mountains), population density and history (200 hab/km^2 in the mountains to 20 hab/km^2 in North Province). In the semi-arid Far North Province, the main crops are rainfed millet and sorghum, transplanted sorghum, cotton, cowpea and rice. The main crop rotations are cotton-cereals or cotton-legumes-cereals. Fallow is rare. Livestock-raising is based on transhumance except in the more densely populated areas (the mountains and the eastern part of the Far North province). The average farm size (2 to 3 ha) is rather small for this kind of region. CA systems have been tested since 2001 in a project implemented by the national cotton agency: SODECOTON (*Société de développement du coton du Cameroon*). The data used in Chapter 2 were obtained from this project. Up to now, CA activities in Cameroon have mainly focused on its application from the point of view of strictly technical management at the village level. To date, few studies have has been undertaken to understand the impacts of CA from field to village levels.

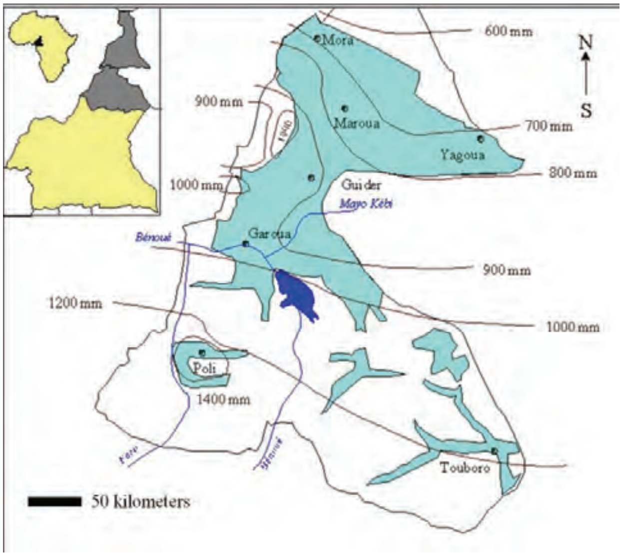


Figure 1.2. The North and Far North Provinces of Cameroon, in blue: land under cotton.

1.2.2 Madagascar

In 1992, the first trial of CA techniques in Madagascar began on KOBAMA industrial farm (state enterprise for wheat production and processing) in Antsirabe, From 1992 to 2011 a Malagasy NGO called TAFA assisted by engineers from CIRAD designed CA cropping systems. From the outset, all the work focused on the technical implementation of CA cropping systems but little scientific research was dedicated to the functions, performance and limitations of CA. Since 2002, more efforts have been invested in studying the effect of CA on erosion (Douzet et al., 2007; Van Hulst et al., 2011), biodiversity (Villenave et al., 2010), crop physiology (Dusserre et al., 2009), pests (Ratnadass et al., 2006), diseases (Sester et al., 2010), weeds (Michellon et al., 2011), socio-economic impacts (Penot et al., 2011a) and crop performance (Charpentier et al., 2005; Rasamizafimanantsoa et al., 2008).

In 2009, around 9,000 farmers were practicing CA in Madagascar and the area under CA was estimated to be close to 5,000 ha across the whole country. In the Lake Alaotra region (Fig. 1.3), the area covered by CA was estimated to be

1,420 ha in 2009 by Rakotondramana et al. (2010) and 971 ha for the same year by Penot et al. (2011). The difference between these estimates of the area under CA come from different perceptions of what constitutes CA. Penot et al. (2011) did not include fields in the first year of application of CA in their estimates, nor fields covered only by forage. Most of the dissemination of CA systems has been done by extension agents financed by public development projects. There is little autonomous diffusion of CA techniques among farmers outside the project network.

Figure 1.3. Madagascar and the Lake Alaotra region (Toamasina province).

1.3 Study objectives and thesis outline

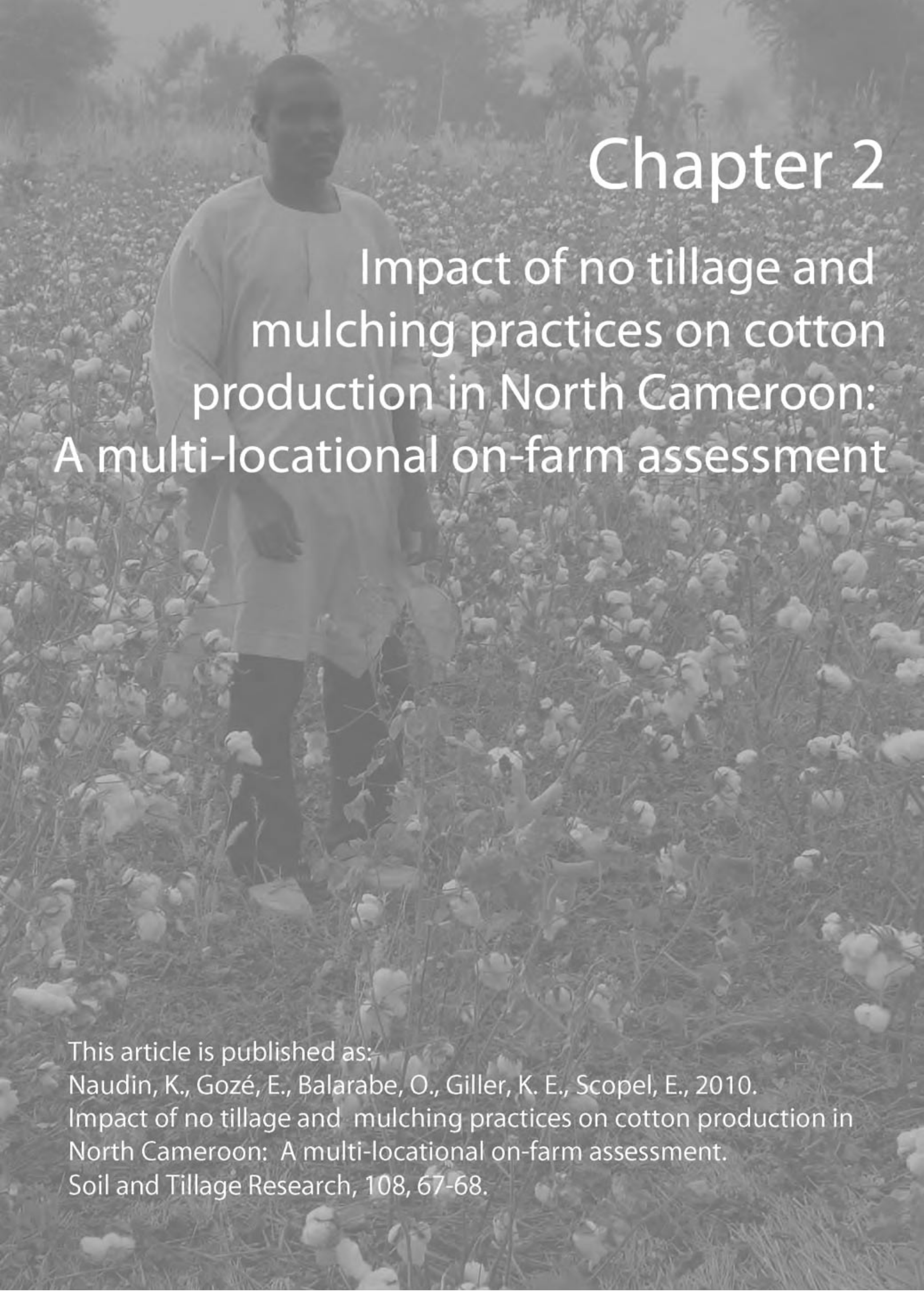
The main hypothesis of my study is:

The benefits of Conservation Agriculture among diverse smallholder farmers are explained by the trade-offs between field and farm level

The specific objectives were to:

1. Compare fibre, grain and biomass production between CA and conventional techniques in small farmer conditions and determine the main environmental and/or technical factors that explain production under different soil management.
2. Quantify biomass production and retention in small farmers' fields to understand the impact of biomass removal on soil cover and linked agroecological functions, and explore their impacts at farm scale.
3. Explore trade-offs and synergies between combinations of CA practices, including biomass removal, and cattle raising for farms under different socio-economic conditions.
4. Formalize agronomic rules and criteria to facilitate the process of CA cropping system design and evaluation in relation to biophysical conditions and farmers' objectives to be evaluated.

In the first experimental chapter (Chapter 2) we explore if it is possible to produce and retain sufficient biomass to implement CA under the semi-arid agroecologies of Northern Cameroon. We also compare cotton and cereal yields with conventional and CA techniques in small farmers' fields (Objective 1). Chapter 3 describes the variability of biomass production for a range of CA systems in farmers' fields in the Lake Alaotra region of Madagascar. Trade-off curves between biomass production, soil cover and agro-ecological functions are derived (Objective 2). Moving from field to farm level, Chapter 4 explores trade-offs and synergies between combinations of CA practices and cattle raising for milk production. Various combinations of cropping systems were compared at farm level, taking into account other components of the farm (labour and cash available, animal production), to achieve farm goals (Objective 3). We explored the impact of the milk market and farm characteristics on the feasibility of CA. In Chapter 5, we formalize the choice of agronomic rules in terms of plant associations or plant successions, at plant and field level (Objective 4). We provide a tool to allow selection of the best crop and cover crop combinations and sequences for CA systems in relation to the impact of bio-physical constraints and famers' preferences. In the final Chapter 6, I explore other agro-ecological functions not tackled in previous chapters, and discuss these in relation to the findings of the earlier chapters. I draw theoretical relationship between biomass removal and agro-ecological impacts at field level such as erosion, pest and disease control, weed control. By drawing these different relationships together we seek to establish threshold requirements for biomass production and removal change in relation to the desired agro-ecological functions. I conclude with a discussion of the implications of our results for the future design of CA for smallholder farming systems in developing countries. I formulate recommendations to implement better balanced research on CA to go beyond traditionally opposing points of view that are often framed as “CA works” versus “CA does not work”.



Chapter 2

Impact of no tillage and mulching practices on cotton production in North Cameroon: A multi-locational on-farm assessment

This article is published as:
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Chapter 2

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Abstract

The applicability of conservation agriculture (CA) in sub-Saharan Africa (SSA) is poorly documented. In the ‘‘Nord’’ and ‘‘Extrême-Nord’’ provinces of Cameroon, in a 2-year rotation between a cereal (maize or sorghum) and cotton, conventional techniques were compared with CA. The study was conducted from 2001 to 2006 in 662 plots in 243 farmers’ fields. Cereal treatments compared were conventional management techniques and CA consisting in the production of mulch using cover crops (*Brachiaria ruziziensis, Crotalaria retusa, Dolichos lablab, Mucuna pruriens, Vigna unguiculata*) intercropped within the cereal. In the ‘‘Extrême-Nord’’ province up to 9.7 t ha^{-1} of vegetative biomass was produced in the CA plots with sorghum and cover crops against up to 4.8 t ha^{-1} for sorghum alone in conventional plots. In the ‘‘Nord’’ province maize + cover crops produced up to 5.2 t ha^{-1} of biomass against up to 2.5 t ha^{-1} for maize alone. In both provinces, the cereal grain yields were equivalent or higher in CA compared to conventional plots. In 18 fields of the ‘‘Extrême-Nord’’ province the mulch remaining the year after sorghum + *B. ruziziensis* is mainly comprised between 3 t ha^{-1} and 5 t ha^{-1}. Cotton treatments compared were T (tillage), NT (no tillage), and NTM (no tillage with mulch). In both provinces these treatments differed in soil cover, number of localized herbicide sprays used, ridging, and amount of nitrogen fertilizer used. In the ‘‘Extrême-Nord’’ province treatments differed also for the number of weeding and the date of the first weeding. In the ‘‘Extrême-Nord’’ province cotton yields were 12% lower for T and 24% lower for NT than for NTM. Cotton yields were regressed on crop husbandry indicators and used inputs. After a manual backward removal in a multiple linear regression respectively no parameters were found to significantly influence yield for T, only one parameter for NT, the number of herbicide sprays used at sowing, and three parameters for NTM: difference between heavy clay and silty loam, application of NPK fertilizer, sowing date. In the ‘‘Nord’’ province no difference in cotton yield was observed between T, NT and NTM. The flowering period was longer for NTM *vs* NT in the ‘‘Extrême-Nord’’ and the ‘‘Nord’’ provinces and NTM *vs* T in the ‘‘Nord’’ province, respectively 13, 9 and 8 days. Although we show that CA techniques can have benefits at field level, further studies are needed to assess their suitability at farm and village levels.

2.1 Introduction

Conservation agriculture (CA) has potential to support crop production under tropical conditions while mitigating natural resource degradation (Benites and Ofori, 1993; Fowler and Rockstrom, 2001; Lal et al., 2007; Sá et al., 2009). CA is defined by three factors: minimum mechanical soil disturbance, permanent organic mulch covering the soil, and diversified crop rotations (Reicosky, 2007; FAO, 2012a). Cotton is already grown with CA techniques in USA (Arriaga et al., 2006) and Brazil (Scopel et al., 2004b). CA has been reported to give increased cotton yields after 6–8 years of application (Nyakatawa and Reddy, 2001; Boquet et al., 2004) but also to depress yields after 2–3 years (Brown et al., 1985; Arriaga et al., 2006) compared with conventional tillage. On large-scale farms in the Americas, the land area under CA has increased rapidly because it has reduced soil erosion and production costs (Seguy et al., 1996; Scopel et al., 2004a; Bolliger et al., 2006; Derpsch, 2007). On the contrary, smallholder farmers in Africa face serious difficulties in applying CA (Knowler and Bradshaw, 2007; Giller et al., 2009). Among the constraints to successful deployment of CA we can cite the difficulty to produce sufficient biomass in areas with low rainfall (Erenstein, 2003); difficulty to retain residue on the field during dry season because of fire, domestic use and cattle grazing (Erenstein, 2003); difficulties with pest and weed control (Brevault et al., 2007, 2008); increased labor demands (Giller et al., 2009) and lastly the technical skills of the farmers to manage CA systems (Benites and Ofori, 1993). In the northern provinces of Cameroon cotton is the only major cash crop, grown by 95% of farmers (Sodecoton pers. com., 2005). Nowadays these farmers face three main constraints. First, the average cotton yield has declined steadily since the 1980s at a rate of -8.4 kg ha^{-1} $year^{-1}$ (Fig. 2.1, Sodecoton unpublished data).

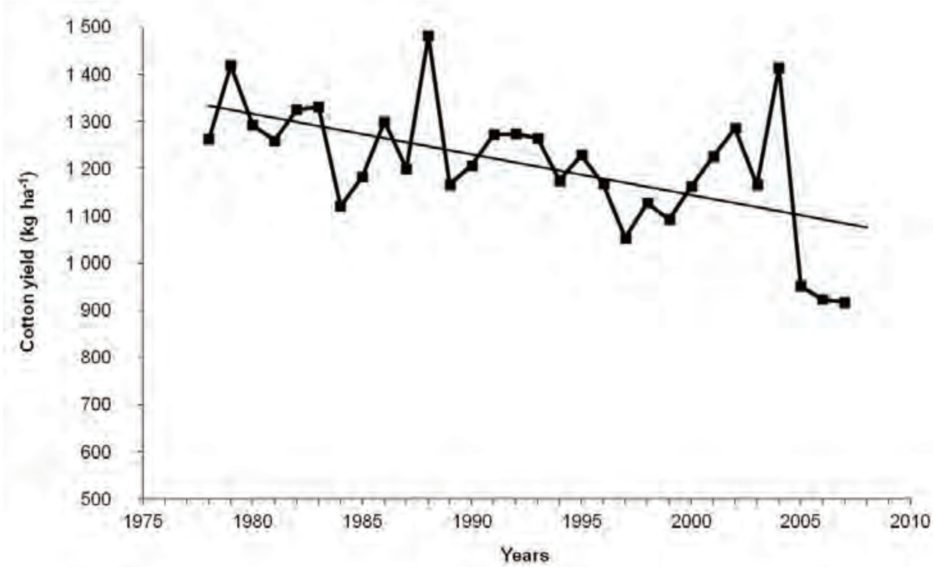


Figure 2.1. Mean cotton yield from 1978 to 2007 for ‘‘Extrême-Nord’’ and ‘‘Nord’’ provinces. (Data provided by Sodecoton). Line: tendency, -8.4 kg ha^{-1} year^{-1}.

Second, the cotton price paid to farmers is decreasing (Folefack et al., 2009), whilst the cost of inputs, and in particular fertilizer and pesticides has increased (Kadekoy et al., 2009). Third, the land area available for cropping area per capita has declined due to increase in population and the restricted land resource (*i.e.* 45% of the ‘‘Nord’’ province area is covered by national parks and game reserves (Labonne et al., 2003). Therefore to maintain their income, farmers need to increase yields and of course this increase should be sustainable. To tackle this productivity and sustainability problem, Sodecoton, in collaboration with CIRAD, explored the possibility of producing cotton based on CA principles, since no references were available on CA cotton cropping systems in Africa. Rather than relying in experimentation in controlled plots on experimental stations, we tested CA in comparative experiments in farmers' fields to assess the feasibility and the impact of CA under farmer's management in the Northern provinces of Cameroon. The main aims were to compare conventional practices with CA, using CA methods as close as possible to current practice, encouraging farmers to operate freely with only technical advice from Sodecoton technicians. The most commonly practiced rotation in north Cameroon is cereal in year *n* followed by cotton in year *n* + 1. In CA plots cereals were intercropped with a cover crop to produce extra biomass in year *n* and in year *n* + 1 cotton was cropped without tillage and with soil cover from retained cereal and cover crop residues. Therefore, the option tested was ‘‘in situ produced mulch’’ according to the classification of (Erenstein, 2003). In this study we addressed four specific questions: (i) how much biomass is it possible to produce and to retain when associating a cover crop with a cereal and what is the impact on cereal yield?; (ii) are differences in soil management inducing other differences in farmers’ cotton management?; (iii) is cotton yield increased under no tillage with mulching as compared with no tillage without mulch or with conventional tillage?; and (iv) what are the main environmental or technical factors that explain cotton yield under different soil management techniques?

2.2. Materials and methods

2.2.1. Location

This study was conducted over 5 years (2001–2006) in the ‘‘Nord’’ and ‘‘Extrême-Nord’’ provinces of Cameroon in an area located between the latitudes of the towns of Mora (11°02’N, 14°09’E) and Touboro (7°47’N, 15°21’E). The ‘‘Extrême-Nord’’ province is characterized by a Sahelo-Sudanian climate with a rainy season from June to September (800 mm mean annual rainfall), whereas the ‘‘Nord’’ province has a Sudanian climate with a single rainy season from mid-May to mid-October (1200 mm mean annual rainfall). The average minimum and maximum temperatures during the growing season were 21 °C and 34 °C, respectively. Soils varied between locations and position on the slope. The main soil types found in this two provinces are eutric fluvisols, planosols/gleyic solonetz, ferric luvisols, acrisols, regosols, gleyic luvisols, planosols, leptisols, luvisols, arenosols and vertisols (FAO-UNESCO Map, 1990) cited by (Yerima and Van Ranst, 2005), with texture ranging from fine clay, heavy clay, loam, sandy, sandy loam and silty loam.

2.2.2. Experimental design and treatments

The study was conducted with a network of farmers' fields during the 2001–2006 period (165 in total in the ''Extrême-Nord'' province and 78 in total in the ''Nord'' province). We report results from 2004 to 2006 for cereals and from 2001 to 2006 for cotton. The cropping system studied is cereal, *i.e.* sorghum (Sorghum bicolor (L.) Moench) in the ''Extrême-Nord'' province and maize (Zea mays L.) in the ''Nord'' province, then rotating next year with cotton (*Gossypium hirsutum* L.). Each farmer's field planted was about 2500 m2 in area, which is the standard unit for allocation of fertilizer and pesticides to farmers of the contract company, Sodecoton. For both cereals and cotton we compared conventional and CA techniques in the same field. The fields were divided into two to four plots: in the case of two plots, one was conventional and the other CA; In the case of three plots per field one of the treatments was replicated, either CA or conventional; In the case of four plots two were conventional and the other two CA. Thus, plot size depended on the number of plots per field, either 1250 m2 if two plots, 833 m^2 if three plots, or 625 m^2 if four plots. All cultural operations were conducted by farmers. Technicians gave recommendations only for management of the CA plot. Table 2.1 shows the characteristics of the treatments compared regarding crop sequence, soil and residue management. In conventional plots cereals were grown alone without associated plants. Residues were managed in the traditional way, *i.e.* usually grazed partially and then burnt. These plots were cropped either with (T) or without tillage (NT), as farmers often plant cereals and cotton in both northern provinces of Cameroon without ploughing their fields, but also without mulching. On T plots, tillage was done after a significant rain shower with an ox-drawn plough to 10–15 cm depth. On NT plots cotton was sown by hand with a hoe with no disturbance of the soil surface outside the mounds. For both T and NT plots, ridging and weed control were perform by hand with a hoe or mechanically. Mechanical operations are performed with a normal plough or with specialized tools such as a 'ridger' for ridging and a 'sweep' for weed control. In NTM plots weed control was performed by hand or with glyphosate spraying between rows with a protecting shield. Each spray of localized herbicide was done with around 1400 g ha^{-1} of glyphosate. In CA plots the cereal was intercropped with a cover crop (*Crotalaria retusa* L., *Brachiaria ruziziensis* R. Germ. & C.M. Evrard, Dolichos lablab L., Mucuna pruriens (L.) DC, or *Vigna unguiculata* (L.) Walp.). The cereal spacing was kept constant across CA and conventional plots: 0.8 m between cereal rows, 0.5 m between mounds and 2 plants/mound on average. The second year cotton was sown without tillage on the residual mulch. Remaining residues from the previous crop, *i.e.* cereal and cover crop, were retained on the soil surface. Plots were partly protected from grazing by a live fence and from fire by a firebreak. Cotton was sown by hand with a hoe with no disturbance of the soil surface outside the mounds. Only in the first year of the rotation some plots were tilled, *e.g.* year *n*: maize + *B. ruziziensis* tilled, year *n* + 1: cotton not tilled, *n* + 2: maize + *B. ruziziensis* not tilled, *n* + 3: cotton not tilled, etc. Cereal treatments included in this study were sorghum in the ‘‘Extrême-Nord’’ province and maize in the ‘‘Nord’’ province, in both cases either grown as sole crop or in association with a cover crop (either *B. ruziziensis* or *C. retusa*). Although other cover crops were compared we do not report the results as the number of repetitions was too small. We aggregated results for cereal tilled and not tilled the first year for two main reasons. First, the number of plots per individual treatment would not have been enough after splitting the sample between the factors: province, type of cover crop, soil management and time of application of CA technique. Second, in this study, our principal aim was to test the effect of intercropping or not with a cover crop on biomass production and cereal yield. Cotton treatments compared were: cotton planted with tillage (T), no tillage without mulch (NT) or no tillage with mulch (NTM), but without separating effects of the previous crop. Table 2.2a shows the distribution of the 112 cereals plots of the survey per province (the ‘‘Extrême-Nord’’ and ‘‘Nord’’ provinces), management technique (associated or not with B. ruziziensis or C. retusa) and years (2004–2006).

Table 2.1. Description of experimental treatments showing crop sequences, intercropped cover crops, soil management methods, and residue management.

Plot	Season						
	Cropping season year *n*			Dry season	Cropping season year *n+1*		
	Crops	Soil management	Treatment name	Residue	Crops	Soil management	Treatment name
Conventional	Cereal* alone	Tillage	Cereal conventional	No residue protection, grazing and burning	Cotton	Tillage	Cotton T
						No Tillage	Cotton NT
		No tillage				Tillage	Cotton T
						No Tillage	Cotton NT
CA	Cereal* + brachiaria	Tillage**	Cereal + brachiaria	Residue protection	Cotton	No Tillage with Mulch	Cotton NTM
		No tillage					
	Cereal* + crotalaria	Tillage**	Cereal + crotalaria				
		No tillage					
	Cereal* + mucuna	Tillage**					
		No tillage					
	Cereal* + dolichos	Tillage**					
		No tillage					
	Cereal* + vigna	Tillage**					
		No tillage					

* Cereal was sorghum in the "Extrême-Nord" province , maize in the "Nord" province

** CA plots were only tilled the first year of the succession, not the third nor the fifth.

Table 2.2b shows the distribution of the 550 cotton plots of the survey by provinces (‘‘Extrême-Nord’’ and ‘‘Nord’’ provinces), soil management techniques (T, NT, NTM) and years (2001–2006).

Table 2.2. Number of single replicate plot comparisons in farmers ‘fields in two provinces ("Extrême-Nord" and "Nord") of Cameroon. a) Number of cereal (sorghum and maize) plots investigated for biomass production, either grown as sole crop (conventional) or intercropped with *B. ruziziensis* or *C. retusa* in each of three years (2004-2006). Each plot where the cereal was intercropped with a cover crop was compared with a control plot where the cereal was grown alone. b) Number of cotton plots investigated for cotton yield under different soil management technique (T: Tillage, NT: No Tillage, NTM: No Tillage with Mulch) over six years (2001-2006).

a)

Province	Treatment	Years			Total
		2004	2005	2006	
Extrême-Nord	Sorghum conventional	5	4	10	19
	Sorghum + brachiaria	5	4	10	19
	Sorghum conventional	5	9	1	15
	Sorghum + crotalaria	5	9	1	15
Nord	Maize conventional	5		4	9
	Maize + brachiaria	5		4	9
	Maize conventional	8		5	13
	Maize + crotalaria	8		5	13
Total		46	26	40	112

b)

Province	Comparison	Treatment	Years						Total
			2001	2002	2003	2004	2005	2006	
Extrême-Nord	T vs NTM	T		11	8	34	17	10	80
		NTM		6	7	33	17	11	74
	NT vs NTM	NT	6	2	15	17	31	41	112
		NTM	6	2	16	18	35	44	121
	None (1 plot per field)	T			4	2			6
		NTM					1		1
Nord	T vs NTM	T	3	1		6	3		13
		NTM	3	1		5	3		12
	NT vs NTM	NT	2	1	4	14	21	17	59
		NTM	2	1	4	15	21	21	64
	T vs NT vs NTM	T				1			1
		NT				1			1
		NTM				1			1
	None (1 plot per field)	T				1			1
		NT				3			3
		NTM						1	1
Total			22	25	58	151	149	145	550

2.2.3. Field measurements

Cereal and cover crop vegetative biomass was cut on 20% of the length of every fifth row (*i.e.* 4% of the field area). Biomass was left to dry for at least 2 weeks in the field before weighing. Cereal grain production was harvested on the same row as biomass but for the full length of the row (*i.e.* 20% of the field area). The length of each row, total number of rows and field width were characterized to extrapolate to an area basis. Mulch quantity on cotton field was estimated using a visual scale at sowing, ridging and harvest. The average of these three dates of observation made the final score we used. The visual scale was previously calibrated by taking pictures and weighing different quantities and types of mulch. For 18 plots of sorghum + *B. ruziziensis* in the ‘‘Extrême-Nord’’ province we had both data of biomass production year *n* and mulch on soil year *n* + 1. On these plots we estimated residue retention from year *n* to year *n* + 1. Cotton technical management was assessed through interviews with the farmer two or three times per month. For each plot, the technician recorded the cropping management characteristics (operation, date, procedure, intensity, products used and amount). Cotton yield was measured by harvesting and weighing cotton seeds on every fifth row (*i.e.* 20% of the field area). The length of each row harvested, total number of rows and field width were characterized to extrapolate to an area basis. Weed pressure was ranked on a visual scale from 0 to 10 (Marnotte, 1984) at sowing, ridging and harvest. In case of heterogeneous weed cover, the plot was visually divided in smaller homogenous parts and the final rank was obtained by a combination of the rank weighted by the respective area. Daily rainfall was recorded in each village with a rain gauge. Soil texture was determined by hand using the VS-FAST method (Mcgarry, 2006) on soil samples taken from 0 to 20 and 20 to 40 cm depths. Start and end of flowering were estimated visually by technicians, and recorded when flowering had started or ended for half of the plants. Not all husbandry indicators were recorded for every plot, depending on the availability of the technician. Thus the comparison between systems was made on a different number of plots for each indicator tested.

2.2.4. Statistical analysis

The comparative experiments were analyzed as multilocation trials, with a linear model for biomass and yield. For the cereal experiment, the following linear model (1) was used:

$$Y_{ijk} = m + a_i + b_j + (ab)_{ij} + E_{ijk} \qquad (1)$$

where m is the intercept, a_i is the effect of treatment i, b_j is the effect of farmer's field j, $(ab)_{ij}$ is their interaction, *i.e.* non-additive part of their combined effect, E_{ijk} is the residual plot effect and measurement error in plot k. For this cereal experiment, after discarding the incomplete farmer's plots, the design was balanced and an analysis of variance was performed for each system compared with the conventional. For the cotton experiment, the design was severely unbalanced and incomplete, as not all the treatments were present in each field. Thus the treatment yield means were adjusted for year and field effects. Since year and field can be considered to be drawn at random in potential populations of years and fields, these control factors and their interactions with the crop management were considered to be random. In addition these random effects on cotton yield were considered to be normally distributed. The parameters of the resulting mixed model were then estimated with the REML method, using the procedure Mixed of SAS/Stat®. The three adjusted means were then compared with three *t*-tests, and the *P*-values adjusted for multiple comparisons using Sidak's method, which is a modification of Bonferroni's method (Hsu, 1996).

For the comparison of treatments, the Gaussian assumption adopted for the effects of year and field on yield are not valid for crop husbandry indicators. Thus the linear model (1) was used, with the *P*-values for *F* obtained with a permutation test. When cotton yields were significantly different between techniques, yields under each technique were regressed separately for each of them, using a set of 10 crop husbandry and environment indicators chosen on the basis of: (i) their hypothesized effect on cotton yield; (ii) avoiding correlation between variables; and (iii) a trade-off between the number of variables and the number of plots analyzed, since not all explanatory variables were recorded in every field. The explanatory variables were: soil texture (fine clay, heavy clay, loam, sandy, sandy loam, silty loam), rain (mm) 2 days before and 10 days after the sowing, number of years of supervision of the field by the project, average weed pressure (average from three ranks at sowing, ridging and harvest), number of herbicide sprays at sowing, number of localized herbicide sprays with a shield after sowing, quantity of P and K fertilizer added (in kg ha^{-1} of P_2O_5); the amount of K was strictly correlated with P since all farmers of the same province used the same NPK fertilizer, quantity of N fertilizer (in kg ha^{-1} of N), average soil cover by residue at sowing (in *t* ha^{-1}), date of sowing (in Julian days). The data were screened to discard very incomplete records and variables. The screening was performed by coding the data presence as binary variable in a plot X variable table, and then simultaneous sorting of variables and plots with the PermutMatrix program (Caraux and Pinloche, 2005). As the remaining table still had missing data, multiple imputations were used to fill in the missing values with random numbers drawn conditionally on the existing data (Rubin, 1996). Multiple imputations were done using procedure ‘mi’ and results analyzed with procedure ‘mianalyse’ of SAS/Stat®. Missing values of qualitative variables (such as soil texture) were not replaced, to comply with the multivariate normal hypothesis underlying the multiple imputation technique. For the comparison of the ‘‘end of flowering dates’’ in the cotton experiment, incomplete farmer’s fields have been discarded. The resulting design was complete and a 2-way analysis of variance was performed with each farmer’s field playing the role of a block. This comparison was performed separately for each province and each conventional technique (T and NT) compared with NTM. All statistical analyses were done using SAS version 9.1.3 (SAS Institute, 2004).

2.3. Results

2.3.1. Vegetative biomass production by cereals and cover crops and cereals grain yields

Total biomass production during the cereal cycle was twice as large on average in CA plots as with conventional management (Table 2.3). This was due to a larger or equivalent biomass production by cereal and to the additional cover crop biomass. In the ‘‘Extrême-Nord’’ province in CA plots sorghum + cover crops produced from 7.5 t ha^{-1} to 9.7 t ha^{-1} of vegetative biomass against 3.5 t ha^{-1} to 4.8 t ha^{-1} for sorghum alone in conventional plots. In the ‘‘Nord’’ province maize + cover crops produced from 4.9 t ha^{-1} to 5.2 t ha^{-1} of vegetative biomass against 1.9 t ha^{-1} to 2.5 t ha^{-1} for maize alone. In the ‘‘Extrême-Nord’’ province both cover crops produced less biomass than sorghum, whilst in the ‘‘Nord’’ province cover crops produced as much vegetative biomass as maize. Sorghum produced more biomass (from 3.5 ha^{-1} to 6.5 t ha^{-1} on average) than maize (from 1.9 t ha^{-1} to 2.5 t ha^{-1}). On average cereal grain yields were moderate and similar under CA or conventional management, ranging from 1.11 t ha^{-1} to 1.51 t ha^{-1} for sorghum in the ‘‘Extrême-Nord’’ province and from 1.69 t ha^{-1} to 2.06 t ha^{-1} for maize in the ‘‘Nord’’ province. Only in the ‘‘Extrême- Nord’’ province was the yield of sorghum associated with *C. retusa* (1.48 t ha^{-1}) greater than for sorghum alone (1.11 t ha^{-1}).

Table 2.3**.** Dry shoot biomass and grain yield (t ha^{-1}) of maize and sorghum grown as a sole crop or intercropped with *B. ruziziensis* or *C. retusa* in the "Extrême-Nord" and "Nord" provinces of Cameroon. Within the same province, same column and each association compared values for conventional and CA followed by different letters are statistically different (ANOVA SAS, $P<0.05$).The standard deviation is given in parentheses.

	Plot	Plant	Cereal vegetative biomass	Cover crop vegetative biomass	Total biomass	Cereal grain yield	Number of plots
Extrême-Nord	Conventional	Sorghum	3.5 (2.1)a	-	3.5 (2.1)a	1.34 (1.17)a	19
	CA	Sorghum + brachiaria	4.3 (2.4)a	3.2 (2.4)	7.5 (4.0)b	1.51 (1.17)a	19
	Conventional	Sorghum	4.8 (2.6)a	-	4.8 (2.6)a	1.11 (0.68)a	15
	CA	Sorghum + crotalaria	6.5 (3.9)b	3.2 (2.8)	9.7 (5.8)b	1.48 (0.95)b	15
Nord	Conventional	Maize	1.9 (0.9)a	-	1.9 (0.9)a	1.80 (0.66)a	9
	CA	Maize + brachiaria	2.0 (1.0)a	3.2 (2.5)	5.2 (2.8)b	1.69 (0.62)a	9
	Conventional	Maize	2.5 (1.0)a	-	2.5 (1.0)a	2.04 (0.80)a	13
	CA	Maize + crotalaria	2.3 (1.0)a	2.5 (1.2)	4.9 (2.1)b	2.06 (0.93)a	13

2.3.2. Residue retention

For 18 plots in the ‘‘Extrême-Nord’’ province we compared biomass production with sorghum + *B. ruziziensis* in year *n* with the amount of residue retained on the soil in year *n* + 1 at cotton sowing (Fig. 2.2). In 14 fields part of the biomass was exported for domestic use or grazed by cattle, despite the plots being protected with live fences. In addition termites consumed part of the remaining biomass. Therefore the quantity of mulch retained in the fields was smaller than the amount of biomass produced the previous year. These fields are below the 1:1 line on Fig. 2.2. In four of the fields, farmers added straw from other fields to increase the mulch cover; therefore the quantity of mulch was greater than biomass produced. These four fields fall above the 1:1 line on Fig. 2.2, but only three points can be seen as two of the points overlay.

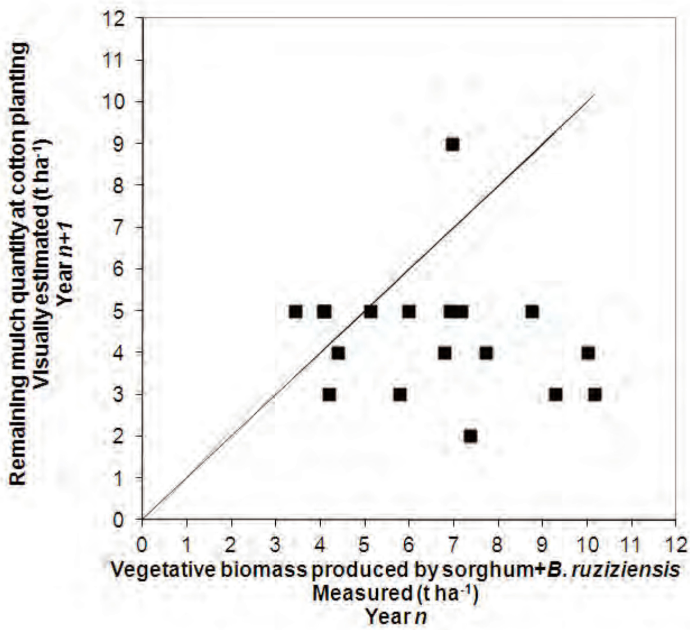


Figure 2.2. Relation between vegetative biomass produced by cereal + cover crop year *n* and mulch on cotton field year *n+1*. Data from 18 plots of Sorghum + *B. ruziziensis*//Cotton rotation in the "Extrême-Nord" Province, Cameroon (2003-2006). The 1:1 line marks the limit between fields where mulch was less

than biomass produced the year before from fields where mulch was more than biomass produced the year before. In most fields a part of the biomass was exported for domestic use or by cattle grazing, thus quantity of mulch retained was less than biomass produced. In 4 fields, farmers added straw to increase mulch cover, therefore the quantity of mulch was greater than the biomass produced.

2.3.3. Farmers' management of cotton production

The farmers' management of T, NT, and NTM treatments did not significantly differ for either the ''Extrême-Nord'' and ''Nord'' provinces regarding the number of herbicide sprays at sowing, sowing date, insecticide sprays, P and K fertilization, and organic manure application (Tab. 2.4). Soil cover was of course less in conventional technique, T or NT, than for NTM, for both the ''Extrême-Nord'' and ''Nord'' provinces. In NTM plots the soil cover was assessed to be 3.5 t ha^{-1} for both the ''Extrême-Nord'' and ''Nord'' provinces. The quantity of mulch remaining in the field was similar in the ''Extrême-Nord'' and the ''Nord'' provinces despite differences in climate and animal or human pressure on residues. Localized spraying of herbicide with a protecting shield was used mainly in NTM plots, for six of ten plots in both provinces compare with one of the ten plots for NT in both province and four of ten plots for T in the ''Extrême-Nord'' province. The number of weeding operations in the ''Extrême-Nord'' province was slightly but significantly less for the NTM (2.6) compared with T (2.8) and NT (2.9) treatments. No difference was found in the ''Nord'' province. The first weeding was performed later in NTM plots in the ''Extrême-Nord'' province (25 days after sowing) against 22 days after sowing for T and 21 days after sowing for NT. No difference was found in the ''Nord'' province. The number of ridgings is different for each technique in for both provinces. The rate of nitrogen fertilizer applied was significantly larger for NTM plots in the ''Extrême-Nord'' province (51.2 kg N ha^{-1} for NTM against 30.3 kg N ha^{-1} for T and 44.6 kg N ha^{-1} for NT). In the ''Nord'' province the difference was similar, *i.e.* 58.9 kg N ha^{-1} for NTM against 52.9 kg N ha^{-1} for NT. More fertilizer was applied by farmers in NTM plots as the technicians recommended they should add more urea to avoid nitrogen deficiency due to mulch.

Table 2.4. Cotton crop management in the two provinces ("Extrême-Nord" and "Nord") under three soil management techniques (T: Tillage, NT: No Tillage, NTM: No Tillage with Mulch). Within the same province, values on the same line followed by different letters are statistically different (ANOVA SAS, Šidák test, *P*<0.10). m.d.: missing data

Provinces	Extrême-Nord			Nord		
Treatment	T	NT	NTM	T	NT	NTM
Number of plots	31	21	53	0	8	10
Soil cover (*t ha^{-1}*)	0.5 a	0.8 a	3.5 b	m.d	0.5 a	3.5 b
Diuron (*Number of sprays*)	0.9	0.9	0.9	m.d	0.4	0.4
Paraquat (*Number of sprays*)	0.3	0.2	0.2	m.d	0.4	0.4
Glyphosate (*Number of sprays*)	0.7	0.7	0.7	m.d	0.6	0.6
Herbicide (*Number of sprays*)	1.9	1.8	1.8	m.d	1.4	1.4
Localized herbicide (*Number of sprays*)	0.4 a	0.1 a	0.6 b	m.d	0.1 a	0.6 b
Weeding (*Number*)	2.8 a	2.9 a	2.6 b	m.d	2.6	2.9
First weeding (*Days after sowing*)	22 a	21 a	25 b	m.d	26	24
Sowing date (*Days after 01Jan*)	157	157	156	m.d	148	148
Ridging (*Number*)	1.0 a	0.5 b	0.1 c	m.d	0.6 a	0.0 b
Insecticide (*Number of sprays*)	6	6	6	m.d	7.1	7.1
N (*kg ha^{-1}*)	30.3 a	44.6 a	51.2 b	m.d	52.9 a	58.9 b
P (*kg ha^{-1}*)	6.6	6.8	6.6	m.d	16.3	15.9
K (*kg ha^{-1}*)	18.8	19.3	18.8	m.d	19.7	19.1
Application of organic manure *(Number)*	0	0	0	m.d	0.1	0.1

2.3.4. Cotton yields

In the ‘‘Extrême-Nord’’ province cotton yields differed significantly (P ≤ 0.10) between the three treatments. Compared with NTM yields were 12% smaller for T and 24% lower for NT (Tab. 2.5). In the ‘‘Nord’’ province no significant differences were found. Yield was then regressed on crop husbandry indicators, separately for each technique. After a manual backward removal of non significant parameters in the multiple linear regression applied on yield (Tab. 2.6), for the T treatment none of the variables significantly influenced yield. For NT only one parameter was significant: the number of herbicide sprays used at sowing was negatively related to cotton yield (-204 kg ha^{-1} per herbicide spray). For NTM three of the ten variables had a significant contribution. First, the difference between heavy clay and silty loam soils: +800 kg ha^{-1} for heavy clay. Second, the application of NPK fertilizers: +32 kg ha^{-1} cotton per kg ha^{-1} of P_2O_5 added (=14 kg ha^{-1} of P). Each kg of P_2O_5 was also supplied together with 1.5 kg of K2O (=1.25 kg of K). Third, the sowing date:-16 kg ha^{-1} of cotton per day of delay in sowing.

Table 2.5. Cotton yields for each province ("Extrême-Nord" and "Nord") under different soil management techniques (T: Tillage, NT: No Tillage, NTM: No Tillage with Mulch). The raw mean is the average of the initial set of raw data. The adjusted mean is the average after adjustment for the year and field effects in this non-orthogonal design. Within the same province, values followed by different letters are statistically different (ANOVA SAS $P \leq 0.01$** and ≤ 0.10*)

Province	Extrême-Nord						Nord		
Treatment	T		NT		NT		T	NT	NTM
Number of plots	86		112		196		17	61	78
Raw mean	1.37		1.08		1.49		1.4	1.46	1.59
Adjusted mean	1.22	ab**	1.06	a**	1.39	b**	1.4	1.45	1.55

* ANOVA SAS P≤0.10, ** ANOVA SAS P≤0.01

Table 2.6. Variation in cotton yield in the "Extrême-Nord" province: multiple linear regression after a manual backward removal of non-significant parameters. Missing data were estimated using multiple imputation (after Rubin, 1996).

Treatment	Nb of plots	Parameter	Estimate	SE	95% Confidence limits		DF	Min	Max	Theta0	t for H0: Parameter= Theta0	Pr > |t|
NT	101	Herbicide at sowing	-204	76	-355	-52	75	-233	168	0	-2.68	0.009
NTM	117	heavy clay - silty loam	800	312	182	1418	114	734	850	0	2.56	0.012
		P and K applied	32	12	9	55	96	27	36	0	2.76	0.007
		Sowing date	-16	7	-30	2	92	-19	-12	0	-2.27	0.025

2.3.5. End of flowering date

In both provinces the flowering period was longer for the NTM treatment than for T and NT. The mean shift is 8, 13, 8, 9 days, respectively for NTM compared to T and NT in the ‘‘Extrême-Nord’’ province and NTM compared to T and NT in the ‘‘Nord’’ province (Fig. 2.3). Differences are statistically significant (P < 0.05) except for NTM vs T in the ‘‘Extrême-Nord’’ province. Our observations indicated that flowering was prolonged in NTM plots because of better resistance of the plants to rainfall shortage. When a dry spell occurred during the growing season the farmers and technicians reported that the production of new flowers stopped on NT and T plots flowering continued on the NTM plot.

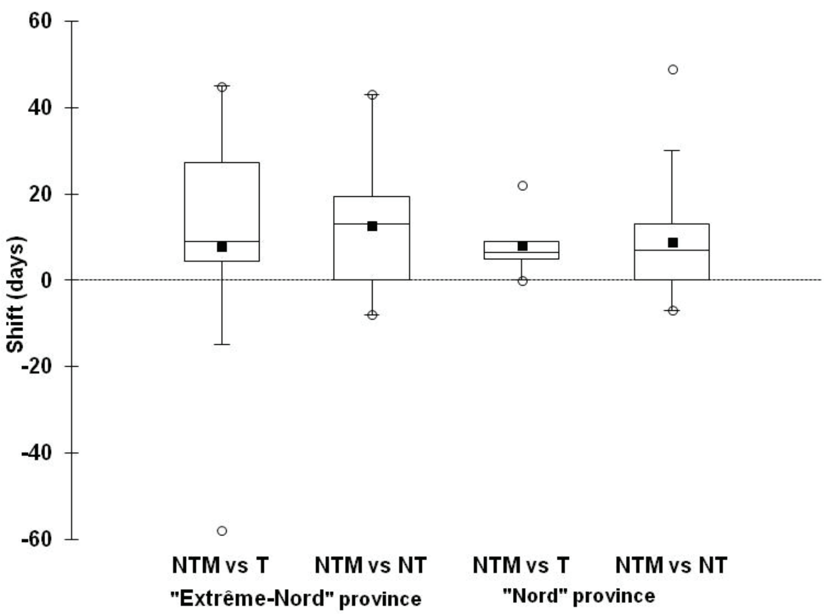


Figure 2.3. Shift in end of cotton flowering date due to NTM as compared to T and NT. "Extrême-Nord" province, NTM vs T, n=10, NTM vs NT, n=23; "Nord" province, NTM vs T, n=6, NTM vs NT, n=42. Box plot: median (continuous line), mean (black square).

2.4. Discussion

2.4.1. Biomass production

The total amount of vegetative biomass produced in farmers' fields was doubled when the cover crops *B. ruziziensis* or *C. retusa* were intercropped with maize or sorghum (Tab. 2.3). Nevertheless, large amounts of biomass production combined with an increased crop off take, may result in nutrient depletion from already poor soils. For example grazing of *B. ruziziensis* without manure or fertilizer input would result in a net loss of soil nutrients. In contrast *C. retusa* is not consumed by cattle and it can improve soil fertility through N_2 fixation (Allen and Allen, 1981). Therefore *B. ruziziensis* should be recommended only for farmers who are able to protect their fields from grazing or who can compensate export of nutrients by bringing back manure or fertilizers. *C. retusa* may be more appropriate for farmers without livestock who do not need additional produce forage and to farmers who cannot protect their fields effectively from grazing.

2.4.2. Biomass retention

Biomass residue retention in the field is the key issue for effective deployment of CA under farmers' conditions in sub-Saharan Africa (SSA) in general (Fowler and Rockstrom, 2001; Erenstein, 2003; Calegari and Ashburner, 2005; Giller et al., 2009) and in both northern provinces of Cameroon in particular. Several authors raised the issue that residue retention is problematic due to the competing uses for residues as feed for free-grazing animals. However, these studies considered only production of residues within conventional mono-cropping systems, and not additional residue produced by cover crops. Our observations show that it was possible to retain both cereal + cover crop residues on the soil surface from year to year under farmers' conditions in SSA. For sorghum + *B. ruziziensis* in the ‘‘Extrême-Nord’’ province on average 67% of total biomass was available at the beginning of the next cropping cycle (Fig. 2.2). The amount of mulch available at cotton sowing was around 3–5 t ha^{-1}.

These amounts are sufficient to have a significant impact on crop water balance and erosion control (Boli Baboule, 1997; Fowler and Rockstrom, 2001; Scopel et al., 2005; Soutou et al., 2005).

2.4.3. Cereal production

No detrimental effect of associating a cover crop on cereal crop yield was observed in this study. Moreover the yield of sorghum was greater when associated with crotalaria, in the ‘‘Extrême- Nord’’ province. Association of cereal with *B. ruziziensis* is more likely to cause a yield decrease than *C. retusa* as its rooting system is similar to that of cereals and both species may compete strongly for water and nitrogen especially under unfertile or limited conditions. Other examples of intercropping of maize with *Brachiaria spp*. come from regions in Brazil where rainfall is higher than in the northern provinces of Cameroon and crops receive more fertilizer (Borghi and Crusciol, 2007; Tsumanuma, 2011). In these cases maize yields were not affected by the presence of *Brachiaria spp*. Observations in farmers' fields indicated that competition can be avoided by proper technical management, by delayed sowing of *B. ruziziensis*, deeper sowing of *B. ruziziensis,* fertilization of maize and early cutting of *B. ruziziensis*. In general competition between cereals and cover crops in CA plots is also reduced by improvement of soil fertility or the water balance and by the cover crop helping to suppress infestation of Striga hermonthica (Del.) Benth (Naudin and Balarabe, 2009).

2.4.4. Weed control

Weed control is one of the main expected advantages of practicing CA. In the ‘‘Extrême-Nord’’ province there was evidence that weed control was improved with NTM indicated by the reduced number of weeding required, and the delay in the date of the first weeding, which allows more flexibility for farmers. Mulch slows down weed emergence, which gives two advantages. First of all it allows farmers to delay the first weeding, which usually overlaps with other operations such as tillage or weeding of other fields (Dounias et al., 2002). Secondly, it reduces weed pressure during the first weeks of the crop when cotton is particularly sensitive to competition from weeds (Deat, 1977; Douti et al., 1995). In conventional systems most of the farmers have to delay the first weeding because they do not have the equipment and animals to weed all fields at the same time. In fact, 80% of farmers who use mechanical weed control have to hire both the plough and draught animals (Vall et al., 2003). In the ‘‘Nord’’ province, weed management variables were not statistically different between T, NT and NTM. In this province which receives more rainfall than the ‘‘Extrême-Nord’’, there is a greater weed pressure and mulch was not sufficient to limit weeds. In Cameroon farmers easily accepted to use localized spraying of herbicide and they recognized the labor and money saving from using herbicide (Olina et al., 2003).

2.4.5. Cotton yields

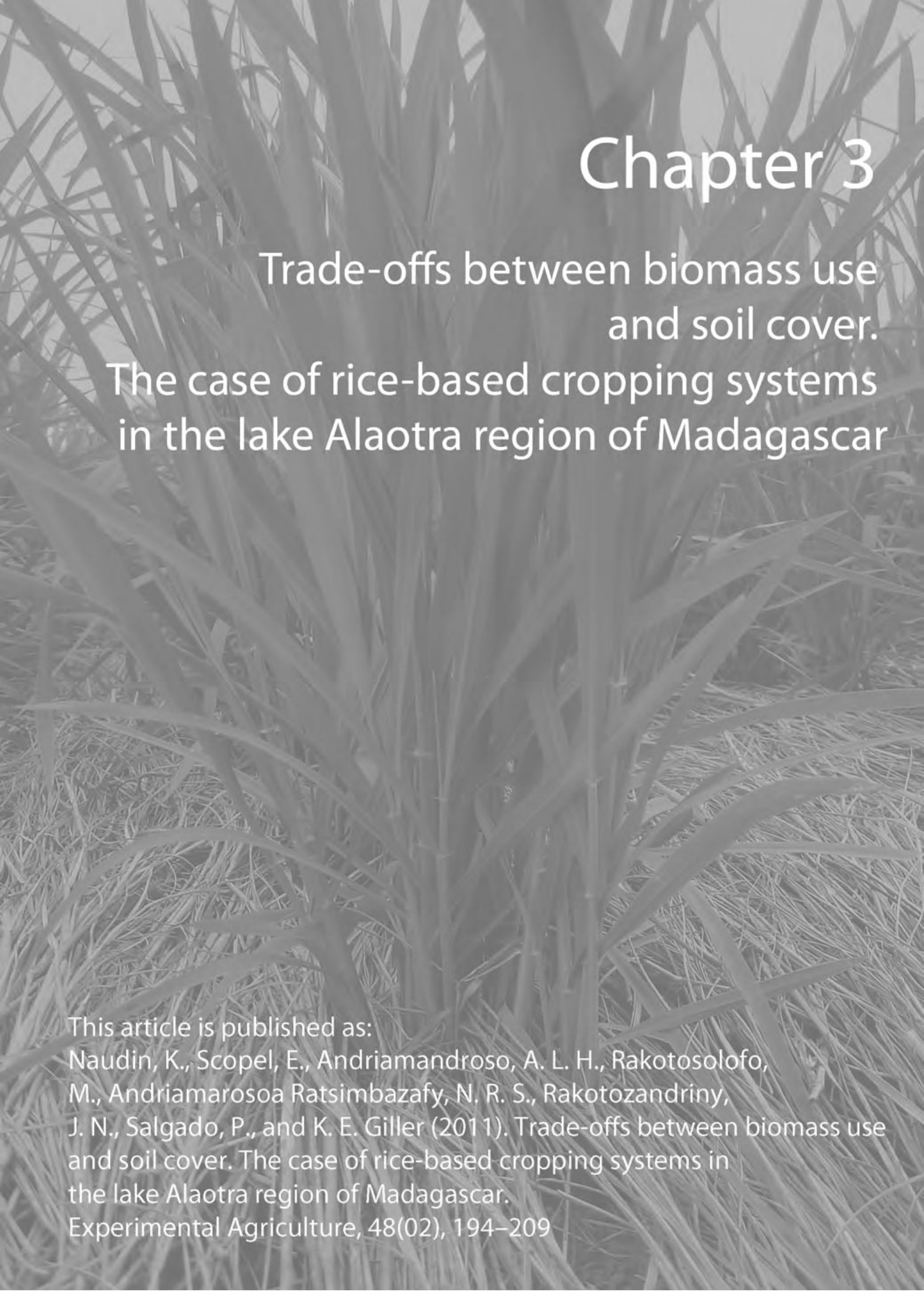
Cotton yields were better with the NTM treatment than with NT and T in the ‘‘Extrême-Nord’’ province. This difference cannot be attributed to the tillage treatments alone but to the whole package applied by the farmers, including an extra 7–21 kg ha^{-1} of N and 0.2–0.5 more applications of localized herbicide with NTM compared with T and NT. In the ‘‘Nord’’ province NTM yields were higher on average in NTM plots than in T or NT but these effects were not statistically different. We conclude that the contrasted effect of NTM, compared with T and NT between the ‘‘Extrême-Nord’’ and ‘‘Nord’’ provinces, was due mainly to different effects of the treatments on water balance as water is more limiting in the drier ‘‘Extrême-Nord’’ province. It was not feasible to directly estimate effects on the water balance in these farmer managed experiments. Moreover it is difficult to quantify the effect of mulch on the water balance although it is well known that mulching practices increase rainfall use efficiency by increasing water infiltration and reducing direct evaporation (Bristow et al., 1986; Findeling et al., 2003). Thus the criterion introduced in the regression, *i.e.* rainfall at sowing, was not selected among the significant parameters after the manual backward removal. Similarly, Bella-Medjo et al., (2005) reported that there was no significant correlation between cotton yield and rainfall in areas receiving more than 600 mm. Few significant parameters were retained in the multiple regression (T: 0, NT: 1, NTM: 3) and the residual yield variability was important, confirming the lack of parameters that characterize the water balance. Among parameters retained in the regression only the sowing date was related with the water balance. NTM cotton yield decreased by 16 kg ha^{-1} for each day of that sowing date was delayed. This yield reduction is less than that reported in the literature where a yield penalty of -20 to -50 kg ha^{-1} per day by which sowing was delayed was found under conventional tillage management techniques (Milleville, 1976; Crétenet, 1987; Lançon et al., 1989; Haggblade and Tembo, 2003). Further indirect evidence of the effect of treatment on the cotton water balance is the difference in the duration of flowering. Because cotton is an indeterminate species its yield is closely related to the length of its reproductive period which is driven by duration of the rainfall period: the longer the reproductive period the greater the yield (Dounias et al., 2002; Blanc et al., 2008). The flowering period was longer for NTM compared to NT in the ‘‘Extrême-Nord’’ and ‘‘Nord’’ provinces, and NTM compared to T in the ‘‘Nord’’ province. The shift is respectively 13, 9 and 8 days. Results acquired in the same area also show a net benefit from the mulch on cotton water balance (Boli Baboule, 1997; Soutou et al., 2005). Beside such short term effects, CA can also have long-term benefits for crop production by reducing soil erosion (Boli Baboule, 1997) and improving the soil fertility (Sá et al., 2009).

2.4.6. CA adoption

CA is often said to be responsible for increased use of chemicals and therefore increased production costs (Affholder et al., 2010). In our case, in the ‘‘Extrême-Nord’’ province, 21 kg ha^{-1} more N and 1100 g ha^{-1} more glyphosate was used, in average, in NTM plots than for T. This additional quantity of fertilizer was equivalent to 12% of the total fixed-charge for 1 ha of cotton (Sodecoton pers. com., 2008 prices). The economic balance is less sensitive to the price of herbicide than that of fertilizer because the additional herbicide used with the NTM technique represented less than 1% of total cost of cropping. These kinds of modifications in crop management often require significant changes in technical and economical support to the farmers (Bolliger et al., 2006; Giller et al., 2009) but in this region farmers are accustomed to using inputs. Thus the northern provinces of Cameroon could be more favorable for CA adoption compared with other SSA regions because: (i) farmers have invested little in equipment for ploughing and in draught animals (Dounias et al., 2002), (ii) direct seeding manually with no tillage is becoming common (in 2005, 50% of the 200,000 ha of cotton were cultivated without tillage (Sodecoton unpublished data)), (iii) farmers are already familiar with the use of herbicides (herbicides were used in 89% of cotton fields in 2007 (Sodecoton unpublished data)), (iv) Sodecoton provides interesting loans and efficient distribution for all fertilizers and pesticides required, (v) Sodecoton actively provides technical advice in all villages of the region. Another key issue for adoption of CA is on-field residue retention. Beside physical management, such as live fences to prevent grazing of crop residues after harvest, the social aspects of land management must be considered. In the northern provinces of Cameroon relationships between sedentary farmers and pastoralists are currently facing profound changes (Labonne et al., 2003). Pastoralists have increasing problems to access land for free grazing due to expansion of agricultural land, national parks and game reserves. CA adoption by farmers should not worsen this situation. Thus technical support is needed not only for the crop farmers but also to cattle owners to improve their forage production and management.

2.5. Conclusion

The CA practices tested in farmers' fields gave improved yield of cotton in the ‘‘Extrême-Nord’’ province with no tillage and mulch but no significant yield benefits in the ‘‘Nord’’ province. These yield increases in the ‘‘Extrême-Nord’’ province could not be attributed to CA alone, as more fertilizer was applied in the CA plots. We observed that technicians and farmers tended to increase the amounts of fertilizer and herbicide used for managing cotton when practicing CA techniques. A factor contributing to the impact was the effect of mulching with CA on the cotton water balance. It was possible to double the amount of biomass produced in farmers' fields using intercropped cover crops without a reduction in the yield of the main intercropped cereal. A large part of this biomass can be retained in the field as mulch for the next crop. Another advantage of CA was that it allowed more flexibility in organization of weeding operations. Further studies are needed to discriminate the impact of all components of the technical system on cotton yield. Whilst this study assessed the impact of CA at field level, and showed that there are potential benefits for smallholder farmers, the question remains as to whether these benefits are sufficiently immediate and tangible for farmers to encourage them to adopt CA practices rapidly. Further studies at farm and village levels are needed to assess whether this management system fits into the farming system as a whole.



Chapter 3

Trade-offs between biomass use and soil cover. The case of rice-based cropping systems in the lake Alaotra region of Madagascar

This article is published as:
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Experimental Agriculture, 48(02), 194–209

Chapter 3

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Abstract

Farmers in the Lake Alaotra region of Madagascar are currently evaluating a range of conservation agriculture (CA) cropping systems. Most of the expected agroecological functions of CA (weed control, erosion control and water retention) are related to the degree of soil cover. Under farmers' conditions, the grain and biomass productivity of these systems is highly variable and the biomass is used for several purposes. In this study, we measured biomass production of cover crops and crops in farmers' fields. Further, we derived relationships to predict the soil cover that can be generated for a particular quantity of mulch. We used these relationships to explore the variability of soil cover that can be generated in farmers' fields, and to estimate how much of the biomass can be removed for use as livestock feed, while retaining sufficient soil cover. Three different kinds of cropping systems were investigated in 91 farmers' fields. The first two cropping sequences were on the hillsides: (i) maize + pulse (*Vigna unguiculata* or *Dolichos lablab*) in year 1, followed by upland rice in year 2; (ii) the second crop sequence included several years of *Stylosanthes guianensis* followed by upland rice; (iii) the third crop sequence was in lowland paddy fields: *Vicia villosa* or *D. lablab*, which was followed by rice within the same year and repeated every year. The biomass available prior to rice sowing varied from 3.6 t ha^{-1} with *S. guianensis* to 7.3 t ha^{-1} with *V. villosa*. The relationship between the mulch quantity (M) and soil cover (C) was measured using digital imaging and was well described by the following equation: $C = 1 - \exp^{(-Am \times M)},$ where Am is an area-to-mass ratio with $R^2 > 0.99$ in all cases. The calculated average soil cover varied from 56 to 97% for maize + *V. unguiculata* and *V. villosa*, respectively. In order to maintain 90% soil cover at rice sowing, the average amount of biomass of *V. villosa* that could be removed was at least 3 t ha^{-1} for three quarters of the fields. This quantity was less for other annual or biennial cropping systems. On average the *V. villosa* aboveground biomass contained 236 kg N ha^{-1}. The study showed that for the conditions of farmers of Malagasy, the production and conservation of biomass is not always sufficient to fulfill all the above-cited agroecological functions of mulch. Inventory of the soil cover capacity for different types of mulch may help farmers to decide how much biomass they can remove from the field.

3.1. Introduction

Conservation agriculture (CA) is defined by three principles: minimum soil disturbance, permanent organic mulch covering the soil and diversified crop rotations and associations (Reicosky, 2007; Hobbs, 2007; FAO, 2012a). Mulch plays an important role in CA benefits. In particular, soil cover acts on (i) weeds control, (ii) erosion control and (iii) improvement of crop–water balance. Weed control, besides allelopathic effects, results from physical effects of mulch on temperature, light extinction and physical obstruction of weed seedling emergence (Teasdale and Mohler, 1993, 2000; Bilalis et al., 2003). The percentage of ground cover has more direct influence than the quantity of biomass on weed emergence (Teasdale and Mohler, 2000), on erosion control (Smets et al., 2008) and on improvements in the crop–water balance (Scopel et al., 2004a). By contrast, other benefits of mulch, such as contributions to increase soil carbon contents (Neto et al., 2010) or provision of nitrogen for subsequent crop growth (Maltas et al., 2009), are directly proportional to the amount of mulch and its content of each element. In the Lake Alaotra region of Madagascar, farmers face different constraints in different fields within their farming systems. In upland fields, soil's organic matter stocks are declining because of reduced fallow time. On these types of fields, dry spells can have a strong impact on crops' yields. In most of paddy fields, rice transplanting is delayed and because of poor water control, weeds threaten rice yield. The average rice yield for conventional fields is around 1 t ha^{-1} for upland rice and 2.5 t ha^{-1} in paddy fields with poor water control (Penot et al., 2010). As part of a long-term research and development program exploring options for enhancing the productivity and sustainability of farming systems in Madagascar, considerable emphasis has been devoted to identify suitable CA systems (Husson et al., 2010). In the Lake Alaotra region, in 2009, 1420 farmers have implemented CA cropping systems on a total of 1000 ha, i.e. on average 0.7 ha per adopting farmer (Rakotondramanana et al., 2010). Extension agents regularly monitor grain production, but biomass production is measured neither in terms of quantity nor in terms of soil cover. Various authors have stressed on the lack of biomass for use as mulch in smallholder farming systems in Africa (et al., 2002; Erenstein, 2003; Giller et al., 2009). First it is difficult to produce enough biomass without external inputs, and second, once biomass is produced, it is difficult to retain it as mulch because of competing uses, especially for livestock feed. Surprisingly, few quantitative data are available concerning mulch availability under smallholder conditions, or on the amount of mulch required to fulfill different ecological functions. To the best of our knowledge, previous research has not addressed the question to what quantity of the available biomass can be removed from field while maintaining a degree of soil cover required for specific agronomic functions. Some authors propose thresholds for biomass exportation but provide few justifications. For example, (Govaerts et al., 2007c) suggest that it is possible to remove 50–70% of the residue while keeping adequate benefits to the soil only considering cereal yields. The hypotheses of this study are that when CA systems are implemented by smallholder farmers, in some cases the production and/or conservation of biomass lead to a partial soil cover; consequently, we can assume that not all cover functions will be effective. We can support farmers and technicians' decisions, in terms of biomass management, by establishing curves taking into relation soil cover and mulch quantity by mulch type.

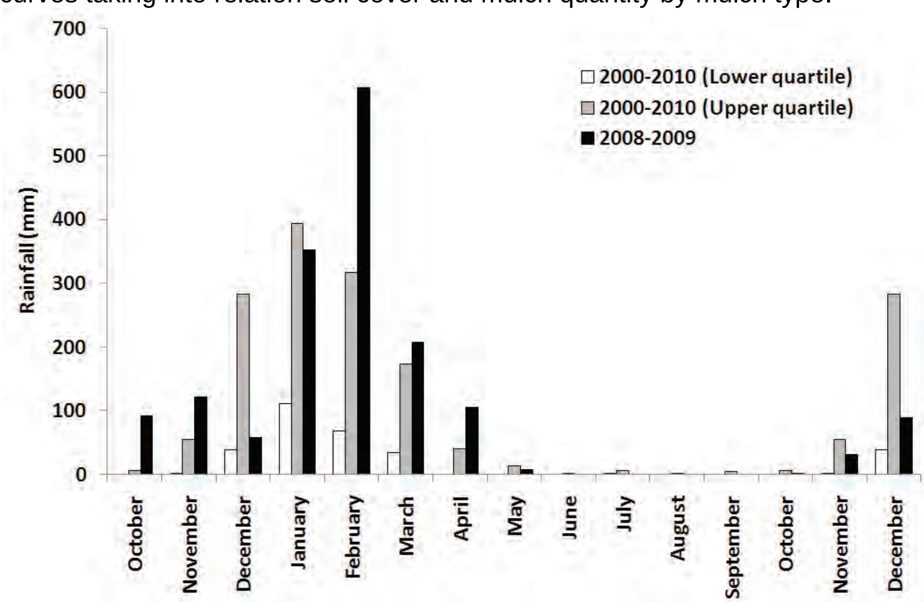


Figure 3.1. Rainfall in the Ambongabe village (48°28'11.2"E, 17°51'50.6"S), lower and upper quartile for the 2000–2010 time period and 2008–2009 season rainfall.

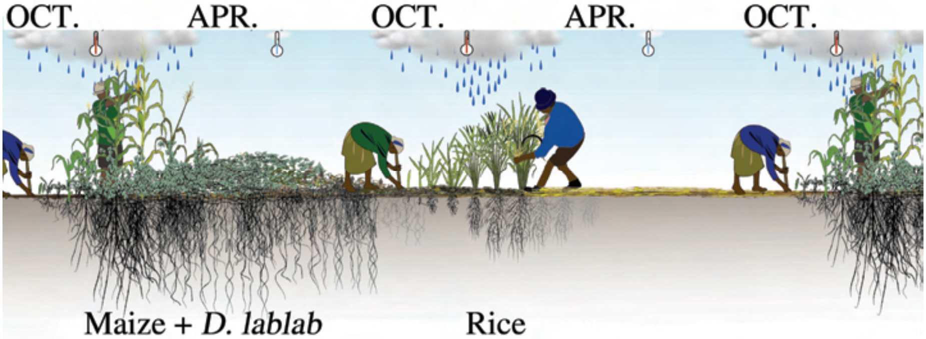
3.2. Materials and methods

3.2.1. Location

All fields investigated were located in the Lake Alaotra region, Madagascar, between 17◦28.0’S and 17◦53.0’S, 48◦08.0’E and 48◦38.0’E, and 760–950 m above sea level. The mid-altitude tropical climate has a mean annual temperature of 22 ◦C. Average rainfall near Ambatondrazaka was 994 mm from 2000 to 2010 and 1553 mm from October 2008 to September 2009 (Fig. 3.1) (Bas Rhône Languedoc (BRL), 2010). The hillside soils are Cambisols (texture 20% clay, 38% silt and 42% sand). Lowland paddy fields are Ferralsols (texture 39% clay, 29% silt and 32% sand) (A. Albrecht, personal communication 2010, Razafimbelo et al., 2010; FAO, 2012b). The hillside soils *C* stocks (0–20-cm layer) are smaller (15.6 to 19.7 t ha^{-1}) than the paddy soils (23.6 to 29.0 t ha^{-1}) (Razafimbelo et al., 2010).

3.2.2 Experimental design

The study was conducted in 91 farmers’ fields in 2008 and 2009. The study was done in one crop cycle but the aim was to stress the intra-annual variability coming from farmers’ management. Cropping systems differ according to their location in the landscape. On the hillsides, locally called tanety, all the crops are rain-fed. In the lowland, paddy field crops are irrigated but with poor water control, as the irrigation network is not fully functional, i.e. the farmers largely depend on rainfall and natural drainage in and out of fields.



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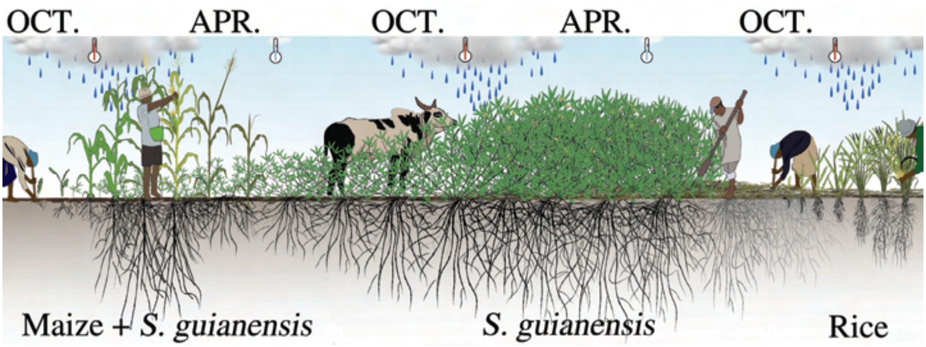

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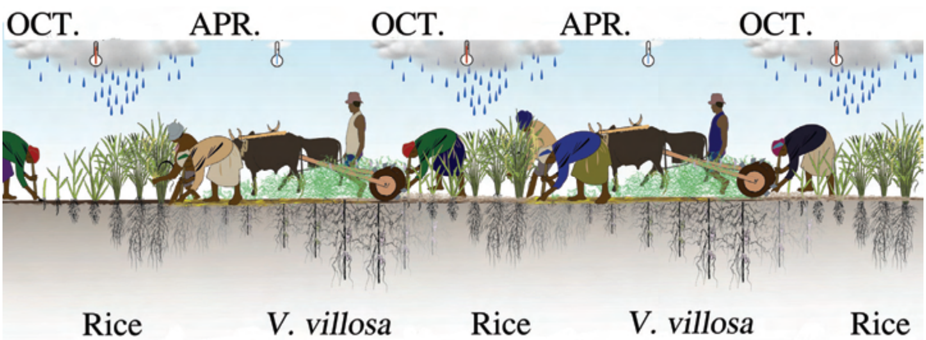


c)

Figure 3.2. Examples of crop and cover crop sequences in CA cropping systems in the Lake Alaotra region, Madagascar. (a) A two-year rotation on hillsides with maize + D. lablab in year n, and upland rice in year n + 1; (b) a multi-annual succession on hillsides with a crop + S. guianensis in year n, S. guianensis alone in year n + 1/2/3, upland rice the last year; (c) a double crop sequence within a year in lowland fields with V. villosa in the off-season and rice in the main season. Modified from Séguy et al. (2009).

Two cropping sequences were studied on the hillsides. The first sequence was maize + pulse in year *n*, followed by upland rice in year *n* + 1. Pulses were cowpea (*Vigna unguiculata* (L.) Walp) or dolichos (*Dolichos lablab* L.), (Figure 3.2a). The second crop sequence included one year of the forage legume *Stylosanthes guianensis* Aubl., 'CIAT 184'. In year *n*, *S. guianensis* was sown alone or intercropped with main crops such as Bambara nut (*Vigna subterranea* (L.) Verdc.), groundnut (*Arachis hypogaea* L.), maize (*Zea mays* L.), and cassava (*Manihot esculenta* Crantz). In year *n* + 1/+2/+3, *S. guianensis* was grown alone for as long as the farmer wished. The last year of rotation, *i.e.* years *n* + 3 or *n* + 4, *S. guianensis* was killed mechanically by cutting the crown. After 2–3 weeks, when the mulch had been flattened, rice was sown (Figure 3.2b). The third sequence studied was in lowland paddy fields with poor water control, where a cover crop was sown during off-season and rice was sown into the mulch of the cover crop at the beginning of the rainy season. The cover crop was hairy vetch (*Vicia villosa* Roth) or *D. lablab* (Figure 3.2c). In all cropping systems rice was directly seeded without tillage. Less than one-fifth of the maize + pulse fields received nitrogen, phosphorus and potassium (NPK) (in ratio of 11:22:16) or urea fertilizer, and in each case less than 50 kg ha^{-1} of fertilizer was used. The season before *V. villosa* and *D. lablab* were grown less than one-fifth of the paddy crops were fertilized. These fields were fertilized with less than 50 kg ha^{-1} urea. Sizes of the fields were diverse but relatively small, ranging from $100m^2$ to $5000m^2$. Farmers conducted all cultural operations. Table 3.1 shows the distribution of fields regarding the crop sequence and their locations.

Table 3.1. Number of fields investigated for each of the crop–cover crop combinations. In four fields, measurements were taken in both 2008 and 2009, giving a total of 95 samples.

Type of fields and cover crop/crop combinations	Number of fields
Tanety (Hillside)	
S. guianensis	17
Maize + *V. unguiculata*	16
Maize + *D. lablab*	22
Paddy fields	
D. lablab	15
V. villosa	21
Total	91

3.2.3 Aboveground biomass measurement

The available biomass was estimated from October to the first week of December, when rice is usually sown. Where biomass was still living (*e.g. S. guianensis* on hillside and *V. villosa* and *D. lablab* in paddy fields) it was cut close at 5 to 15 cm above the soil surface. Where the plants had already senesced (*e.g.* maize + *D. lablab* or maize + *V. unguiculata*), the dead material was removed from the soil to be weighed. Five sub-samples of 1 m2 were taken in each field, one in the centre of the field and others at the middle of each diagonal linking the centre and the corners of the field. Each sub-sample was weighed separately and a composite sample prepared. The composite sample was weighed in the field, air-dried and finally reweighed. Samples of the biomass (200 g) were oven-dried at 55 ◦C for 48 h to allow correction for moisture content and stored for near-infrared reflectance spectroscopy (NIRS) predictions. All biomass values are expressed on a dry matter basis. For some fields of maize + *V. unguiculata* and maize + *D. Lablab*, the aboveground biomass was also measured at the end of the growing season (March–April). At this date, five plots of 2.5 m2 were sampled from each field using the above-described pattern. As the maize rows were spaced 1 m apart, each sample included 2.5-m length of one row of maize.

3.2.4 Soil cover measurement

The relationship between mulch mass and soil cover was determined by measuring soil cover of the known mass of plant residue. Residues of *D. lablab*, *V. villosa*, maize + *D. lablab* mixture and *S. guianensis* were collected from farmers' fields. In order to give uniform background, quantities of residues equivalent to 1, 3, 6, 9, 12 and 15 t ha^{-1} were spread on a 1 m^2 blue plastic tarpauline. A nadir view photograph of the residue was taken. Digital images were processed using the Photoshop ® software to determine the visible area of the blue background. From this we inferred the proportion of the area covered by plant residues. For each quantity of residue, two replicate pictures were taken with a different random arrangement of residues. For randomly distributed mulch elements, the fraction of the soil covered by mulch (*C*) can be related to the mulch mass (*M*) by:

$$C = 1 - \exp^{(-A\,m \times M),} \qquad (1)$$

where *Am* is an area-to-mass ratio depending on mulch type (Gregory, 1982; Scopel et al., 1999; Smets et al., 2008). The coefficient *Am* has physical dimension of area covered by one average straw per mass of one average straw. We determined *Am* by adjusting a non-linear regression to observed data using the 'non-linear regression' function of the XLStat 2010.1.01 software.

3.2.5 Nitrogen content

An NIRS prediction was used to determine the nitrogen content of samples. This method has proved to be an efficient tool to screen the quality of organic resources (Shepherd et al., 2003). Dried samples were finely grounded (1 mm) and scanned twice at 2-nm intervals over the 1100–2500-nm wavelengths on a monochromator (FOSS—NIR Systems 5000, Silver Spring, MD, USA). Mathematical analysis of the spectral data was performed with Win ISI III Version 1.63 software (Infrasoft International, Port Matilda, PA, USA). The NIRS prediction referential used in the present study consisted of a large tropical and temperate forage database pairing reflectance values and reference analyses for concentrations of nitrogen (Tran et al., 2009). The nitrogen content is reported here only for *S. guianensis* on hillside and *V. villosa*, *D. lablab* on paddy fields, as the analysis has been made on biomass sample just before the seeding of rice. Thus, part of the nitrogen content of this biomass is available to following rice through mulch decomposition.

3.3. Results

3.3.1 Production of biomass and amount of mulch available

The mulch available at the end of the dry season (October 2009) compared to the biomass produced at the beginning of the dry season (April–May 2009) was higher for maize + *D. lablab* fields and lower for maize + *V. unguiculata* ones (Figure 3.3). The mean quantity of mulch available prior to sowing of rice on hillsides was 3.6 t ha^{-1} for fields of *S. guianensis*, 4.0 t ha^{-1} for maize + *V. unguiculata* fields and 5.4 t ha^{-1} for maize +*D. lablab* fields. In paddy fields, the mean mulch available was 6.8 t ha−1 with *V. villosa* and 7.3 t ha^{-1} with *D. lablab* (Figure 3.4a). For all types of mulch, there was considerable variability between the hillside fields, but less variability in the paddy fields.

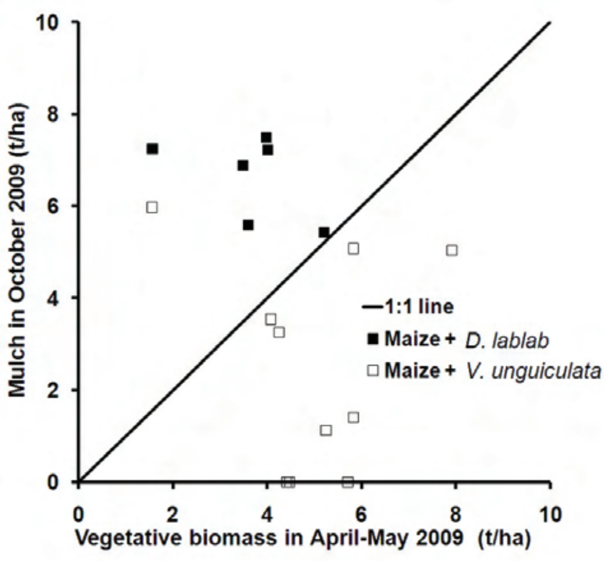


Figure 3.3. Relationship between the amount of vegetative biomass (dry matter) produced by cereal (+ cover crop) in April–May 2009 and the amount of mulch left in October 2009. Data from 17 farmers' fields.

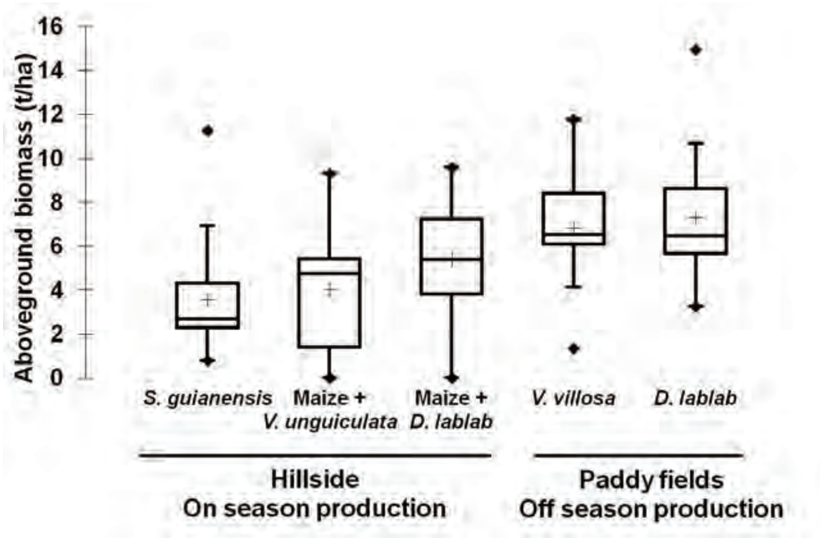
3.3.2 Soil cover

The digital picture analysis allowed relationships between the quantity of mulch and soil cover to be derived for four types of mulch (*S. guianensis*, maize+ *D. lablab*, *D. lablab* alone and *V. villosa*). Equation (1) proved to be a good descriptor of this relationship, as the coefficient of determination between observed soil cover and curve fit was greater than 0.99 in all cases (Figure 3.5a). *Am* for maize + *D. lablab*, *D. lablab*, *S. guianensis* and *V. villosa* are presented in Table 3.2. The capacity of plant residues to cover the soil varied strongly between different residues. For example, 3 t ha^{-1} of maize + *D. lablab* covered around 50% of the soil surface, 3 t ha^{-1} of *D. lablab* covered 60%, whereas a similar quantity of *V. villosa* biomass covered nearly 90% of the soil surface. Ninety-five percent of soil cover was obtained with less than 5 t ha^{-1} of *V. villosa*, but the same cover rate required 10 t ha^{-1} of *D. lablab.* The range of biomass quantity (Figure 3.4a) was then converted to soil cover (Figure 3.4b) using Equation (1) and the *Am* values given in Table 3.2. The calculated average soil cover (lower and upper quartile between commas) for *S.*

guianensis, maize + *V. unguiculata*, maize + *D. lablab*, *V. villosa* and *D. lablab* was 66% (58–79%), 56% (30– 74%), 70% (62–84%), 97% (99–100%) and 87% (84–94%), respectively. The range of variability observed for mulch quantity was different from those of soil cover. For example, CV of the average quantity of mulch of *V. villosa* was 34%, but the CV for soil cover was only 8%. For maize + *D. lablab* cover the CV varied from 27 to 41% (Figures 3.4a, b).

Table 3.2. Area-to-mass ratio values (*Am*) from this study and from the literature for different crops and cover crops.

Crop and cover crop	Type of residue	Area to mass	Source
Avena sativa	Not decomposed	1.370	Steiner et al., 1999
	Unknown	1.400	Gregory, 1982
Dolichos lablab	Not decomposed	0.320	This study
Glycine max	Unknown	0.720	Gregory, 1982
Hordeum vulgare	Not decomposed	1.170	Steiner et al., 1999
Secale cereale	Unknown	0.420	Teasdale and Mohler, 2000
Stylosanthes guianensis	Not decomposed	0.377	This study
Triticum aestivum	Unknown	0.540	Gregory, 1982
	Unknown	0.450	Gregory, 1982
Triticum aestivum	Not decomposed	1.830	Steiner et al., 1999
Triticum aestivum	Not decomposed	1.380	Steiner et al., 1999
Vicia villosa	Not decomposed	0.690	Teasdale and Mohler, 2000
	Not decomposed	0.742	This study
Zea mays	Not decomposed	0.114	Gilley et al., 1986
	Unknown	0.190	Teasdale and Mohler, 2000
	Unknown	0.400	Gregory, 1982
	Not decomposed	0.367	Scopel et al., 1999
	Partially decomposed	0.271	Scopel et al., 1999
	Partially decomposed,	0.092	Scopel et al., 1999
Zea mays +	Partially decomposed	0.251	This study



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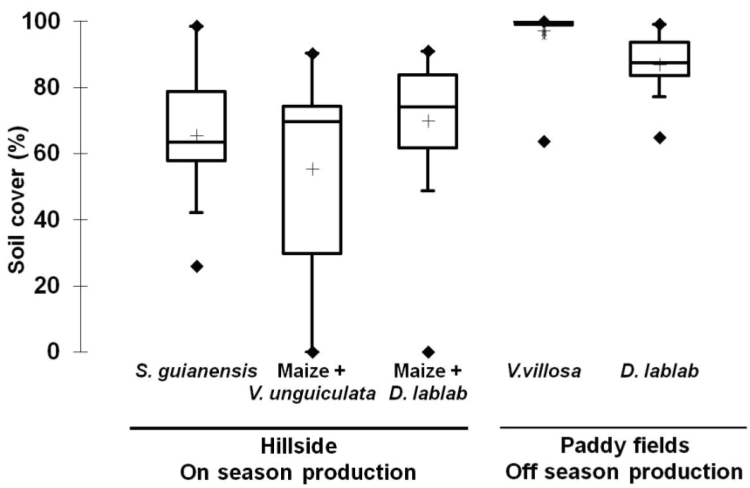


b)

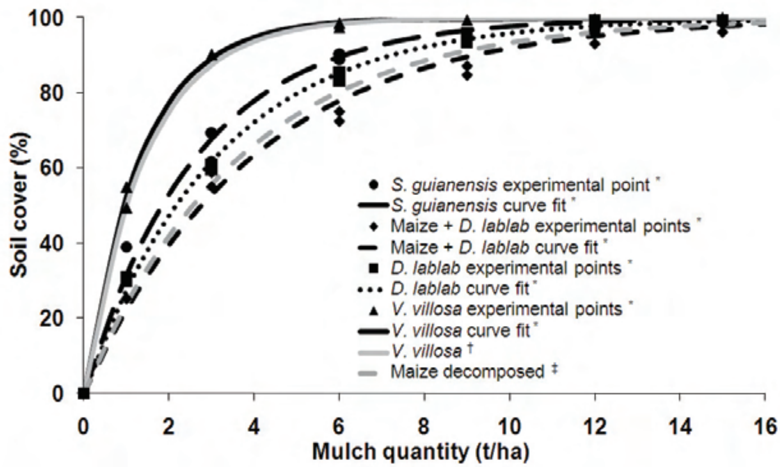
Figure 3.4. (a) Aboveground dry biomass available as mulch prior to sowing of rice. (b) Soil cover calculated from the amount of biomass measured in the field. Measured in the hillside fields and paddy fields in the Lake Alaotra region, 2008–2009. Number of fields (*n*): *S. guianensis* = 19; maize + *V. unguiculata* = 17; maize + *D. lablab* = 23; *V. villosa* = 21; *D. lablab* = 15. Box plot: median (horizontal continuous line), mean (cross).

3.3.3 Impact of biomass removal on soil cover

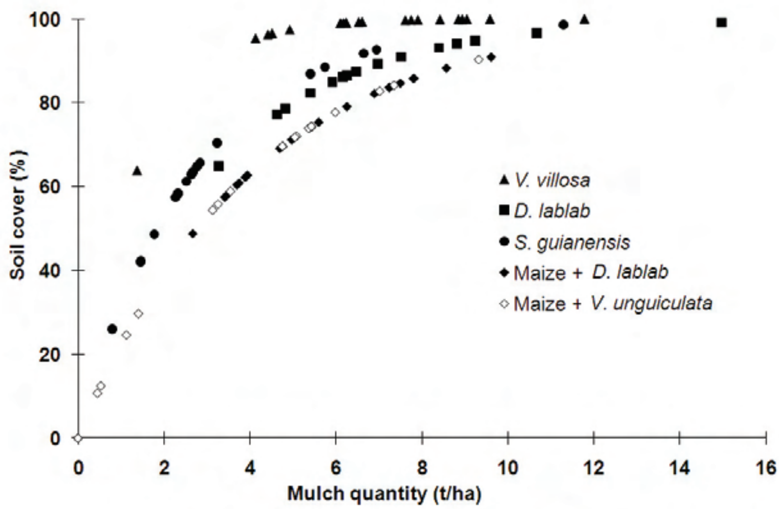
Using the biomass production of *V. villosa*, *D. lablab*, *S. guianensis*, and maize + *V. unguiculata* measured in the field (Figure 3.4a) and the soil cover curves derived from this data (Figure 3.5b), estimates were made of the effects of biomass removal on soil cover (Figure 3.6). This was done using the upper and the lower quartiles of biomass production among farmers' fields. For *V. villosa*, points A, B, C and D mark the maximum quantity of biomass that can be removed before reaching 90% of soil cover (A, B) or 30% (C, D), for three quarters of fields (A, C) or one quarter of fields (B, D). For three quarters of the *V. villosa* fields, 3 t ha^{-1} can be removed while maintaining 90% soil cover, and 5.6 t ha^{-1} can be removed from one quarter of the fields (Figure 3.6). If the target is 30% of soil cover, then the removable biomass will be 5.6 and 7.9 t ha−1 for three quarters or one-quarter of the fields, respectively.

3.3.4 Nitrogen content

The average nitrogen content of samples was respectively 2.7% of dry matter for *S. guianensis*, 3.4% for *V. villosa* and 1.8% for *D. lablab*. Combining with total biomass available, this gave 82 (±21) kg N ha−1 in the mulch for *S. guianensis*, 236 (±97) kg N ha−1 for *V. villosa*, and 123 (±46) kg N ha^{-1} for *D. lablab* (Figure 3.7).



a)



b)

Figure 3.5. a) Soil cover (%) as a function of the amount of mulch for different crop/cover crop combinations. (*) data from this study, (†) data from Teasdale and Mohler, (2000), (‡) data from Scopel et al. (1999). Equation: $C = 1 – \exp^{(-Am.M)}$ Where (C) is the fraction of the soil covered by mulch, (M) the mulch mass in t ha^{-1} and Am is an area-to-mass ratio depending on mulch type. The R^2 for the fitted curves are respectively 0.991, 0.990, 0.998 and 0.998 for *S. guianensis*, maize + *D. lablab*, *D. lablab* and *V. villosa*. b) Soil cover calculated from the quantities of biomass measured in the field. The relation between mulch quantity and soil cover for maize + *V. unguiculata* has been inferred from the relation for maize + *D. lablab*. Number of fields: *S. guianensis*, n = 19; maize + *V. unguiculata*, n = 17; maize + *D. lablab*, n = 23; *V. villosa*, n = 21; *D. lablab*, n = 15.

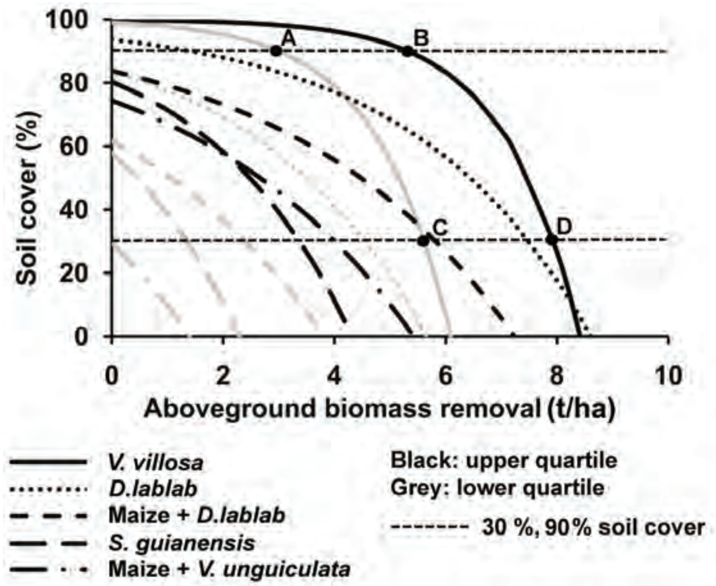


Figure 3.6. Effect of biomass removal on the soil cover for five different cover crops, *V. villosa*, *D. lablab*, maize + *D. lablab*, *S. guianensis* and maize + *V. unguiculata* and quartile values from farmers' fields. Point A, B, C and D, mark the maximum quantity of dry biomass which can be removed while maintaining 90% soil cover (A, B) or 30 % (C, D), for 3/4 of the fields (A, C) or 1/4 of the fields (B, D). Theses quantity are 3.0, 5.3, 5.6 and 7.9 t ha^{-1} for A, B, C and D, respectively.

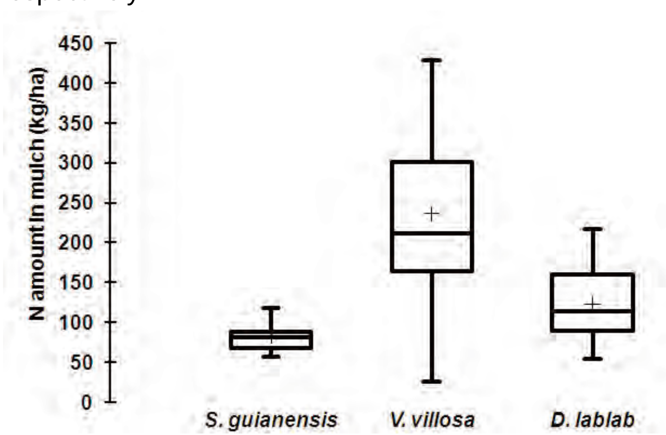


Figure 3.7. Amount of nitrogen (kg ha^{-1}) contained in the aboveground dry biomass of the different cover crops. Number of fields: *S guianensis*, n = 5; *V. villosa*, n = 21; *D. lablab*, n = 15. Box plot: median (continuous line), mean (cross).

3.4. Discussion

3.4.1 Production and conservation of biomass

Although maize + *D. lablab* fields had more biomass at the end of the dry season than at the beginning, less biomass remained in almost all maize + *V. unguiculata* fields. Three reasons can explain the difference between these two cover crops. First, *V. unguiculata* had ceased to grow before the end of the rainy season, whereas *D. lablab* continued to grow into the dry season. Second, cattle herders tend not to graze their cattle in fields of maize + *D. lablab* fields, as they see *D. lablab* is still growing there. As all the standing biomass dries *in situ* in maize + *V. unguiculata* fields, herders consider it to be a ‘normal’ field available for grazing. Third, farmers grew *D. lablab* only to produce biomass for the next crop, and not for edible grain. By contrast, farmers grew *V. unguiculata* for grain with the additional benefit of biomass for use as mulch. Nevertheless, the amount of biomass remaining at the end of the dry season in the Alaotra region of Madagascar is large compared with CA systems in other countries of sub-Saharan Africa, *e.g.* 3.5 t ha^{-1} (Naudin et al., 2010) or 2 t ha^{-1} (Wezel et al., 2002). *S. guianensis* can be cut and killed at the beginning of the third year after sowing to produce mulch where rice can be sown (Husson et al., 2010). All *S. guianensis* fields investigated were in the third, fourth or fifth year but the average biomass available at the beginning of the subsequent rainy season was 3.6 t ha^{-1}, a small amount compared with the other cover crops, and much less than reported elsewhere (*e.g.* Saito et al., (2010) reported 7.4 t ha^{-1} for a two-year stand in Benin). Under controlled conditions, *S. guianensis* produced from 5 to 20 t ha^{-1} (Husson et al., 2008), but under real farmers’ conditions most of these fields had been partially grazed during the dry seasons, which explained the relatively small amount of remaining biomass. *S. guianensis* is well known to support multiple cuts during the growing season to provide fresh forage for animal feed, and is resistant to grazing (Roberge and Toutain, 1999). Nevertheless, this reduces its final growth and biomass available. Furthermore, *S. guianensis* is usually grown on the worst fields where farmers intend to improve soil fertility and can afford to leave the field uncropped. The 2008–2009 cropping season was rainy season (1553 mm) compared with the average rains (994 mm), thus the biomass obtained on hillsides was close to the optimum attainable in this region. Biomass production on paddy fields should be less sensitive to this climatic condition, as the water is not limiting in this kind of fields. In the lowland paddy fields, biomass production of *D. lablab* and *V. villosa* was similar at around 7 t ha−1, and greater than reported earlier in the literature, *e.g.* 2.44 to 5.16 t ha−1 (Sainju et al., 2006). None of these *V. villosa* or *D. lablab* fields have been grazed. Farmers prefer to grow *V. villosa* in this kind of field, as it can be intercropped with vegetables. *V. villosa* requires more water than *D. lablab*, so it is found only in lower lying fields with fine soil texture that allow capillary rise. When water is more limiting, *D. lablab* is selected.

In the Lake Alaotra region of Madagascar where no basal fertilizer is applied, large amount of legume biomass was achieved in the lowland fields, but less biomass was produced in the upland fields probably due to poorer soil fertility. In particular, this poor production can be linked with low phosphorus availability. In many parts of the tropics basal fertilization with phosphorus and other nutrients is required to get good legume growth and nitrogen fixation (Giller and Cadisch, 1995). In paddy fields, the use of adapted legumes (*D. lablab* and *V. villosa*) on relatively fertile soils allowed production of a large amount of biomass each year without competing with other crops. The paddy fields are usually under exploited during the off-season, as vegetables are the only crops grown where manual irrigation is possible. The area covered by vegetables is small due to the labor required, leaving a large area where cover crops could be grown.

3.4.2 Relationships between biomass and soil cover

The capacity of plant residues to cover soil varied strongly between different residues. The presence of small leaves in *V. villosa, S. guianensis* and *D. lablab* gives the higher *Am* value compared with cereal residues alone so that much less biomass is needed to obtain the same percentage of soil cover. The digital picture analysis proved to be a useful tool for generating predictive equations to relate biomass with soil cover for different residue mixtures (Figure 3.5a). This method is relatively easy to use even with low resources. It should be used more in order to better characterize mulch characteristics and thus to allow a better explanation for CA cropping systems impacts.

As we can see in Figure 3.4a, the variability in terms of biomass production is relatively high, as is commonly found in smallholder cropping systems in developing countries (Tittonell et al., 2008; Naudin et al., 2010). This variability results in a wide range of soil cover (Figure 3.4b) and nitrogen input (Figure 3.7). These examples demonstrate the wide variability in biomass yield found under farmer's conditions, even for one type of cropping system, so that the agronomic benefits expected from CA are not necessarily fulfilled. Further, the agronomic benefits are not linearly linked with the quantity of mulch and therefore thresholds should be defined for specific combinations of environmental conditions, cover crop and expected function.

3.4.3 Maintaining sufficient mulch

We can infer from Smets et al., (2008) that a minimum of 30% soil cover is required to reduce inter-rill soil erosion substantially, whereas a target of 90% is the minimum required to obtain a good weed control (Teasdale and Mohler, 2000; Bilalis et al., 2003). The amount of mulch required to achieve these rates of soil cover can be readily derived from Figure 3.5a. On the hillside fields where the biomass production was less than in the lowland paddy fields, the amount of biomass that could be removed was substantially less. For example, for *S. guianensis*, 90% of soil cover was reached in less than a quarter of the fields. With a target of 30% of soil cover, the removable biomass was between 1.4 t ha^{-1} for three quarters of the fields and 3.4 t ha^{-1} for a quarter of the fields. Thus, the amount of biomass that can be removed for livestock, or grazed *in situ* varies strongly between the hillside and lowland paddy fields and between different legumes or residue mixtures. Govaerts et al., (2005) stressed the need to establish critical amount of residue required for maintaining soil productivity while using part of the biomass as fodder. These authors also mentioned that zero tillage with residue retention give better cereal yield results than without residue. But they did not specified the quantity of mulch retained and even less the percentage of corresponding soil cover. Knowing the relationship between potential removable biomass and impact in terms of soil cover rate can help farmers to take decisions regarding the possibility to use part of the biomass produced in field. It also helps to compare the management flexibility of different cropping systems. In fact, in no-till cropping systems, the lack of mulch, less or equal to 30% of soil cover, can lead to increased erosion (Volk et al., 2004) and weed competition (Bilalis et al., 2003) compared with tilled cropping.

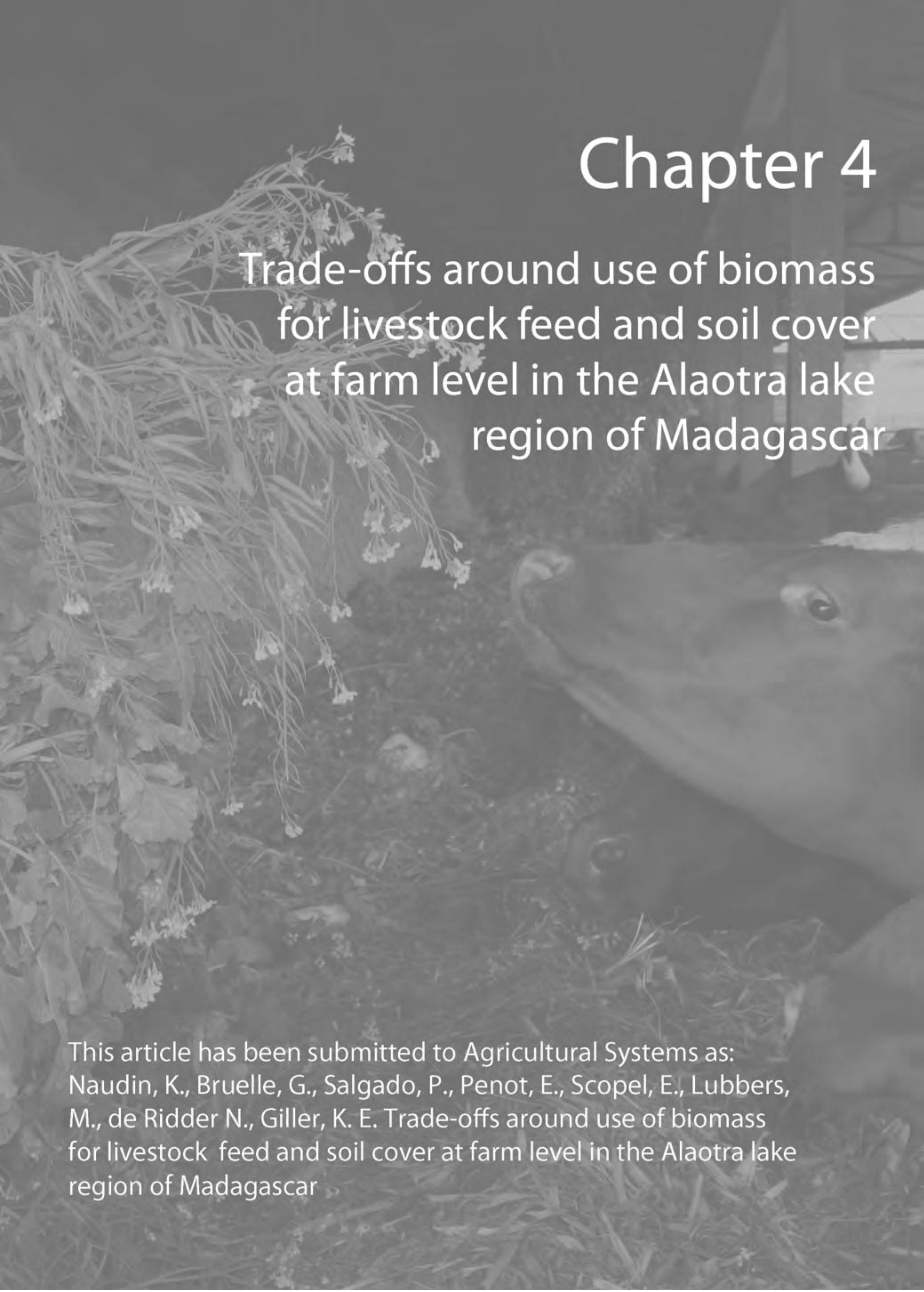
3.4.4 Nitrogen availability and role on short-term productivity and long-term fertility

Beyond the quantity of biomass produced, the quality also varies among cover crops and fields. Again, for the same types of field (paddy field) and cropping system (annual rotation with rice), the quantity of nitrogen available in the residues can double with the type of cover crop, *e.g.* 123 kg N ha−1 for *D. lablab* against 236 kg N ha−1 for *V. villosa*. Values for *V. villosa* are higher than those observed by (Sainju et al., 2006), which varied from 76 to 167 kg N ha−1 depending on the year. These authors showed that even with the smaller amount of biomass added, the available inorganic nitrogen content increased in the soil when *V. villosa* was killed resulting in increased grain and biomass yields of the subsequent sorghum crop. The biomass nitrogen can be partially returned to soil to benefit the following rice crop, or be fed to cattle to improve animal productivity. As stressed by (Rufino et al., 2006), the direct application of plant materials to soil results in more efficient cycling of nitrogen, with fewer losses from the system than from materials fed to livestock and then returned to the soil through manure. However, livestock provide many other benefits, and animal manure can contain large amount of available nitrogen, which can promote crop growth in short term (Rufino et al., 2006). The partial allocation of the biomass to cattle or to mulch is driven by the goals of the farmer; especially by trade-offs between expected benefits from rice yield improvement, reduction in labor required for weeding and enhanced cattle production. The short-term effects of mulch, such as water balance improvement (Scopel et al., 2004a;

Thierfelder and Wall, 2010) are more easily perceived by farmers than long-term effects on soil fertility. Although after eight years of implementation of CA in the Lake Alaotra region, the *C* stock was consistently greater in CA plots (between 1.1 t ha^{-1} and 3.5 t ha^{-1}) than in ploughed plots, but the difference was not statistically significant (Razafimbelo *et al.*, 2010). Furthermore, these results were obtained when all of the plant residues were returned as mulch in the CA plots (rarely achieved in farmers' fields) compared with complete removal of crop residues in the ploughed plots. These results reinforce the conclusion that the fulfillment of agroecological functions by CA will depend on the amount of biomass returned to soil and length of time the system is implemented.

3.5. Conclusion

Our results showed that it is possible to produce and keep sufficient biomass in the field for CA systems even under smallholder farming conditions where livestock graze freely during dry season. However, the quantity of biomass produced varies strongly between hillsides and valleys, and between cover crops and farmers' management. Soil cover is not linearly related to mulch quantity. Thus, for a given quantity of biomass exported to feed cattle, the impact is different depending on the cover crop, the initial amount of biomass and the agroecological functions of mulch searched by farmers. When comparing benefits of different types of CA cropping systems, it is important to report the amount and quality of biomass produced, and the corresponding rate of soil cover. In terms of the agroecological functions of soil cover, such as weed control, erosion control and water retention, different amount of mulch is required with different cover crops. The relationships between biomass export for cattle feed and these agroecological functions require more systematic study. The decision on how much biomass can be removed from the field will depend on the local biophysical conditions, the biomass characteristics and the farmer's goals for his/her whole farm system.



Chapter 4

Trade-offs around use of biomass for livestock feed and soil cover at farm level in the Alaotra lake region of Madagascar

This article has been submitted to Agricultural Systems as:
Naudin, K., Bruelle, G., Salgado, P., Penot, E., Scopel, E., Lubbers, M., de Ridder N., Giller, K. E. Trade-offs around use of biomass for livestock feed and soil cover at farm level in the Alaotra lake region of Madagascar

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Abstract

Conservation agriculture (CA) is promoted as a promising technology to stabilize or improve crop yields in Africa and Madagascar. However, small scale farmers face difficulties to retain soil cover; mainly because of competing uses for the biomass produced, especially to feed cattle. To explore the relation between dairy cow raising and CA we developed an optimization model at farm level. Our aim was to explore trade-offs and synergies between combinations of CA practices and the size of dairy cow herds. Our model includes three main components: the farm, the crops and the cattle herd. The optimization was made on the total net income for three years. Biomass produced by cropping activities can either serve as mulch or to feed cows. We applied a constraint on the minimum soil cover % to keep at the end of each year for CA fields: from 30 to 95 %. We simulated two scenarios of milk market: a small milk market with low forage price and an open milk market scenario with higher price of forage. Three kinds of farms were simulated: medium-sized farm with hillsides dominating, medium-sized farm with paddy fields dominating and small-sized farm with hillsides. Changing the degree of soil cover to be retained on CA plots did not significantly modify the total farm net income. It was more strongly influenced by the characteristics of the milk market. In case of a limited milk market it was not profitable to have more than seven cows because the expenses were not compensated by animals' products. In most of the situation simulated above six/seven cows the model chose to introduce CA cropping systems producing more forage on the hillsides if we allow the model to implement CA with only 30 % of soil cover. Conversely when setting this constraint to 95 % the model chose not to implement CA on hillsides. In all of the situations simulated with the maximum number of cows (12) it was possible to keep at least 50 % of soil cover on 80 % of the hillsides fields. On the other hand, it was impossible to keep 95 % of soil cover when forage fetched a high price. Overall, CA systems can be beneficial for dairy cow farmers due to the forage produced, although the milk market and thus the value of biomass for forage, has a strong influence on the way CA can implemented at field level.

Keywords: biomass uses tradeoffs, soil cover, forage, crop residues, smallholder, linear programming

4.1. Introduction

Conservation agriculture (CA) is a promoted as a promising technology to control soil erosion and stabilize or improve crop yields in Africa and Madagascar (Fowler and Rockstrom, 2001; Hobbs, 2007; Schutter, 2011). Big part of CA efficiency is linked to the physical and chemical ecological functions played at the field level by a permanent superficial mulch of residue. The physical functions relating to soil cover include: i) weed control (Teasdale and Mohler, 2000), ii) erosion control (Smets et al., 2008), and iii) improvement of the crop water balance due to promotion of infiltration and reduction of evaporation losses (Scopel et al., 2004a). The chemical effects include provision of nutrients for plant growth and provision of chemical buffering for nutrient retention and against soil acidity, due to inputs of organic matter and nutrients (Maltas et al., 2009; Neto et al., 2010). However, small scale farmers face some difficulties to retain an organic mulch as soil cover when implementing CA (Erenstein, 2003; Giller et al., 2009). This is due to two main issues; first, it is difficult for them to produce sufficient biomass on poor soil without fertilizer; and second, there are competing uses for the biomass produced, especially for livestock feed. In the present study we compare the relative advantages of using biomass produced on-farm as forage resource to feed the cattle or as a mulch to cover and protect the soil in the context of Malagasy small scale farmers. We focus on the short-term effects of mulch, which are mainly related to soil cover. Short-term benefits include weed control and yield increasing through crop water balance improvement. We developed an optimization model GANESH (Goals oriented Approach to use No till for a better Economic and environmental sustainability for SmallHolders) for simulation on representative, small and medium-sized farm using multiple goal linear programming. We used this model to explore the relation between dairy cows raising, a range of CA practices and biomass uses with economic income optimized at farm level. This has been done for two scenarios of milk market conditions and three kinds of farms. Our aim was to explore trade-offs and synergies between combinations of CA practices and the size of dairy cow herds.

4.2. Materials and methods

4.2.1 Model

4.2.1.1 General description

The model includes three main components: i) the farm, ii) the crops, iii) the cattle herd (Figure 4.1a). External factors taken into account in the model were: input price (pesticide, fertilizer, hired labor, forage), output price (milk manure, crop production) and volume of milk marketable. GANESH optimizes the total net income of the farm (from crop and livestock activities) over a three year period, by choosing: i) the crop succession to be implemented on each farm fields, by selecting among 28 crop production activities which can be combined in different ways for the three-year period; ii) the quantity of forage to be purchased from outside the farm; iii) the quantity of above-ground biomass exported from the field for cattle feeding; iv) the quantity of hired labor. Constraints applied to the optimization are (Fig. 4.1b): i) the size of the workforce available in the family and the labor which can be hired taking into account available cash; ii) a minimum soil cover % at the end of each year for CA fields. This value can be set between 30 to 95 %; In this study, the minimum was set to 30 % of soil cover, a value commonly accepted to be the minimum for effective organic mulching (Erenstein, 2003). If the biomass exported for cattle feeding leads to a soil cover lower than the chosen value, then the following crop production activities must be conventional and not CA; iii) a minimum net income to cover basic needs of the farm (including household requirements); iv) a maximum volume of milk marketable per day.

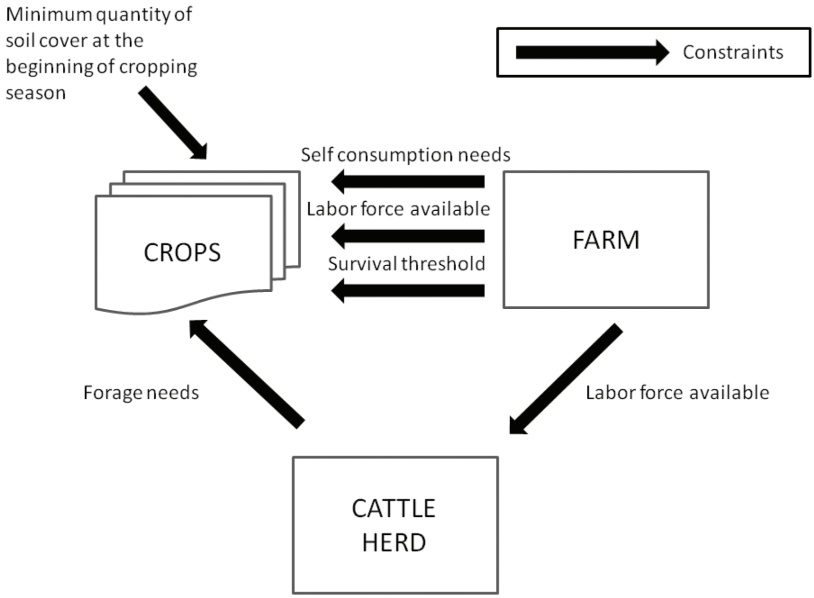

Figure 4.1a. The three main components of the GANESH model (Crops, Farm and Cattle herd) and the main constraints influencing the choice of crop and cattle production activities and farm income.

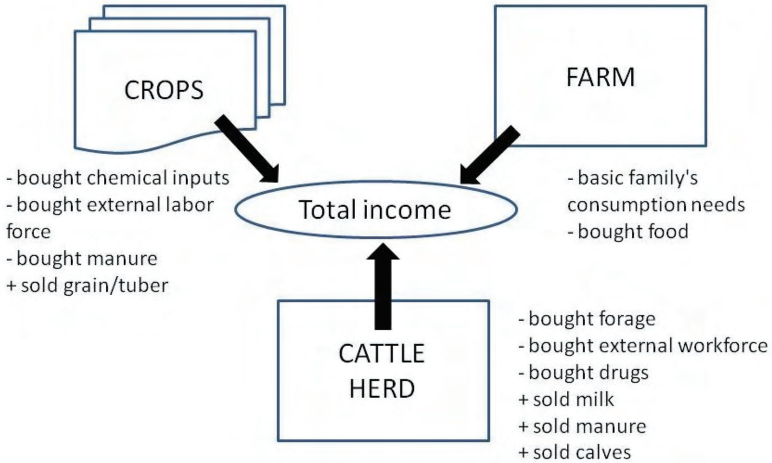

Figure 4.1b. A schematic representation of the objective function optimized in the model to maximize the total net income of the farm (from crop and livestock activities) for three years, and its dependence on the positive (+) or negative (-) contributions of the different variables.

4.2.1.2 Farm

The farm is characterized by the number and type of people (for calculating household food demand and the workforce available): people > 60 years, men >15 years, women > 15 years, children < 15 years, children at school. Usually when people have cattle they employ a permanent worker (cowherd) to take care of the animals. These workers do not appear as part of the available workforce in the model as their time is strictly devoted to care of the cattle, but their salaries are taken into account as a cost.

4.2.1.3 Crops

Crops are taken into account in the model as crop production activities, which include either a crop alone or a crop associated with a cover crop (Tab. 4.1). The duration of the crop production activities is one year, (*i.e.* including both the rainy season and the off-season). Thus some crop production activities include only one crop or cover crop (*e.g.* rice alone grown with conventional techniques) or two (*e.g.* rice/vetch, meaning rice during the rainy season and vetch during the off-season). There are 28 crop production activities spread among four different kind of fields: i) hillsides, locally called *tanety*, ii) alluvial soils, locally called *baiboho*, iii) lowland paddy fields with poor water control, and iv) irrigated paddy fields. Hillsides soils typically have a loam texture (Razafimbelo et al., 2010). They are usually devoted to upland crops such as cassava, maize and groundnuts. Baiboho soils have a sandy loam texture (Razafimbelo et al., 2010). All upland crops can be grown on alluvial soils (upland rice, sweet potatoes, maize) during the rainy season. During the off-season, legumes or cover crops can be grown thanks to a shallow water table. Poor water control paddy fields and irrigated paddy field typically have a sandy loam texture. They are devoted to irrigated rice during the rainy season. During the off-season a vegetable or a cover crop can be grown depending on the soil texture and the depth of the water table. Crop production activities are split between conventional and CA soil management techniques. When looking for the optimal solution (see below for optimization) GANESH seeks to find the best crop production activities succession over the full three years for each field. CA systems can only start in Year *n+1* as they require biomass production in Year *n* to serve as mulch. However, the implementation of CA systems in Year *n+1* require that all, or part, of the aboveground biomass produced in year *n* is retained in the field (complying the minimum soil cover constraint set). Therefore, in general, in Year 1 of the simulation it is impossible to implement CA as no biomass has been produced previously. But, in some case CA systems can start in the off-season of Year 1 if enough biomass is produced and retained from the rainy season. GANESH combines crop production activities over a rotation period of three years with set goals and constraints. For example, a feasible crop succession for an alluvial soil field is: Year 1: maize in the rainy season, *D. lablab* in the off-season both with conventional techniques; Year 2: rice in the rainy season and vetch in the off-season both with CA techniques; Year 3: rice in the rainy season and vetch in the off-season both with CA techniques. The period of three years was chosen to allow full rotation cycles, to focus only on short terms effect of CA (weed control and yield increase due to better water balance) and to limit the number of crop production activities combinations to prevent excessive run times. Agronomic rules were incorporated to prohibit or force some crop successions. For example *S. guianensis* should be intercropped with a crop in year *n*. It takes at least one year to produce sufficient aboveground biomass, thus it occupies the field for, at least, the whole of year *n+1* to be able to cultivate another crop in CA in year *n+2.*

Table 4.1. Crop production activities are the basic building blocks in the construction of cropping systems. They differ for each of the four types of fields (irrigated paddy fields, poor water control paddy fields, alluvial soils, hillsides) and are managed with either conventional or CA techniques. As CA techniques require biomass production the year before these crop production activities can only be grown in years 2 and 3. Conventional crop production activities can be grown in years 1, 2 and 3. "/" between two crops means a within-year (intra-annual) sequence of two plants between the rainy season and the off-season.

Type of field	Soil management	Crops (+cover crops)	Year 1	Year 2	Year 3
Irrigated paddy fields	Conventional	Irrigated rice	X	X	X
Poor water control paddy fields	Conventional	Rice/Fallow	X	X	X
		Rice/Vetch	X	X	X
	CA	Rice/Fallow		X	X
		Rice/Vetch		X	X
Alluvial soil	Conventional	Rice/Fallow	X	X	X
		Rice/Dolichos	X	X	X
		Rice/Vetch	X	X	X
		Maize/Fallow	X	X	X
		Maize/Dolichos	X	X	X
		Maize+Dolichos/Fallow	X	X	X
	CA	Rice/Fallow		X	X
		Rice/Dolichos		X	X
		Rice/Vetch		X	X
		Maize+Dolichos/Fallow		X	X
Hillsides	Conventional	Brachiaria	X	X	X
		Cassava	X	X	X
		Groundnut	X	X	X
		Groundnut+Stylo	X	X	X
		Maize	X	X	X
		Maize+Dolichos	X	X	X
		Rice	X	X	X
		Cassava+Brachiaria	X	X	X
	CA	Brachiaria		X	X
		Rice		X	X
		Groundnut+Stylo		X	X
		Maize+Dolichos		X	X
		Stylo		X	X

The labor requirements for each crop production activities (Appendix 1) are defined by a number of man/day on a 2-weeks time step. The inputs requirements of crop production activities including seeds quantity, chemical fertilizer and organic manure, pesticides (Appendix 2) were translated into monetary values in kAr (1 kAr= 0.36 Euros in average in 2011). There are 12 kinds of outputs of the crop production activities (Appendix 3): rice grain, maize grain, cassava tuber, groundnut, vetch residues, dolichos residues, maize stover, maize stover + dolichos residues, brachiaria, stylosanthes, rice bran, rice straw; plus one “additional” output which is stored maize stover, meaning maize stover taken to the farm to feed cattle and not left in the field to be grazed. Part of these outputs can be used to feed cattle: vetch residues, dolichos residues, maize stover, maize stover + dolichos residues, brachiaria, stylosanthes, rice bran, rice straw, stored maize stover. One further product not produced in the fields, namely cut natural grass, can be used to feed cattle. The entire set of technical coefficients was derived from repeated farm and plot survey described below. The forage chemical composition and nutritive values of each of these products were measured in a previous study (Naudin et al., 2011; P. Salgado et al., unpublished results). The forage nutritive value is expressed according the French system by UFL (Unite Fourragère Lait) and PDI (Protéine Digestible dans l’Intestin grêle) to describe the energy and protein values, respectively (INRA, 2007; Appendix 4).

The relation between mulch quantity and soil cover as described by Gregory (1982) was calibrated locally (Naudin et al., 2011c). This relationship is used to: i) calculate the remaining quantity of biomass to cover soil at the end of the dry season after partial consumption of residue by animals; ii) determine if the remaining soil cover at the end of the dry season in year *n* is sufficient to implement CA in year *n+1*. We used an integer variable and not a continuous’ one for the area of fields. In fact, farmers in this region do not split fields into many small parts so we set to 10 the maximum number of fields per type of soil. In the simulation process we also set to 500 m^2 the minimum field area.

4.2.1.4 Livestock

The livestock component comprises four kinds of animals: zebu male, zebu female, local dairy cow breed (Rana) and improved dairy cow breed (Norwegian Red). The inputs for these production activities are the labor requirement to take care of animals, forage nutritive value expressed as energy (UFL/kg DM) and protein (g PDI/kg DM) values in which feed intake was limited by the potential feed intake (kg DM/day) of animals. The outputs are milk, manure, heifers and calves sold, and draught power (Appendix 5). The herd management function of GANESH is dynamic, *i.e.* the age of each animal is set at the beginning of the simulation process, and then the age changes over the three year periods of simulation with a two-week time step (*e.g*. an animal age of 36 months at the beginning of the simulation is aged 72 months at the end). The animal feeding aspect is a key part of the model since it gathers at the same time the production (milk and draught power) and the management of forage and crop residues resources. The approach used by the model is based on the total cover of energy requirements of the herd. Energy requirements are calculated according to the expenditures for maintenance, growth (calves, heifers), pregnancy, and production. These requirements are met by both forage resources produced on-farm (first priority but under a certain number of nutritional or physiological constraints) and feeds (forage) coming from market. The energy requirements for lactation are calculated for a fixed milk production level (according to the month of lactation and genetic type) and will have obligatorily to be met by the energy supply of the ration. Animals are never considered as in under-nutrition situation. The maximum feed intake capacity of animals is taken into account by the model. The minimum feed intake is fixed to 75% of the maximum feed intake. Rice straw is mainly used to meet the minimal fibber requirements of animals. Feed requirement (biomass quantity and energy) increases with age and production stage of the animals (Appendix 5). To simplify interpretation of model outputs we decided to set to 12 months the productive cycle of cows: 10 months of lactation period and 2 months of dry period. Data for animal requirement and production were derived from standard tables (INRA, 2007; Rasamizafimanantsoa et al., 2008).

4.2.1.5 External parameters and optimization

To be able to simulate different scenarios, GANESH includes the influence of external parameters such as: the maximum volume of milk marketable/day, hired workforce price for each year period, selling price for each agricultural product including milk, price of inputs for crop production, prices of all purchased goods. The GANESH model is written in GAMS (22.5.148) with an Excel 2003 interface. It includes 24 variables and 51 equations, (Appendix 6).

4.2.2 Data from Madagascar

Data were derived from yearly repeated survey of more than 1000 farms which received technical advice from the development agency Bas Rhone Languedoc (BRL). The survey revealed a great diversity of technical management of crops among the farmers (Domas et al., 2008).

4.2.3. Scenarios explored

4.2.3.1 Milk market

We simulated two scenarios in terms of milk market. The first scenario corresponds to the actual situation in the Lake Alaotra region (Saint-André, 2010): essentially only low potential dairy cows (Rana breed) are available, high milk price (1.2 kAr/l), low grass prices (0.1 kAr/kg DM), but limitation in terms of milk volume marketable per day due to a small market (we set to 20 l the maximum volume to be marketable per day for each farm). The second was a scenario close to the current situation in the Vakinankaratra region 300 km south from Lake Alaotra (Duba, 2011) which represents one of the most important regions for milk production in Madagascar. Thus the second scenario was: availability of improved dairy cows breed (such as Norwegian Red), low milk prices (0.5 kAr/l), higher grass prices (0.2 kAr/kg DM), but no limitation in terms of the milk volume marketable per day.

4.2.3.2 Three kinds of farms

Based on previous studies (Penot et al., 2011a) we decided to simulate three kinds of typical farms which differ in land area in hillsides and irrigated paddy fields. These are important differentiating factors that are essential to farmers' self-sufficiency in rice. The three kinds of simulated farms were: i) medium-sized farm with hillsides dominating; ii) medium-sized farm with paddy fields dominating; iii) small-sized farm with hillsides (Tab. 4.2).

The simulations with each farm type differed only in the number of cows raised (from 0 to 12), area of fields and % of soil cover (from 30 to 95%). All other parameters (*e.g.* number of zebu cattle, type of people, etc.) were the same for all farms and simulations. The cowherder's salary was set to 200 kAr/year. A limitation in terms of maximum cassava marketable per year was set to 550 kg/year to avoid the model to choose preferentially this activity as the market is inelastic.

Table 4.2: Number and total area of fields for each simulated farms types.

	Irrigated paddy fields		Poor water control paddy fields		Alluvial soil		Hillsides	
	Area (ha)	No. of fields	Area (ha)	No. of fields	Area (ha)	No. of fields	Area (ha)	No. of fields
Medium-sized farm with hillsides	0	0	1	10	0.5	8	2	10
Medium-sized farm with paddy fields	1	10	1	10	0.5	8	1	10
Small-sized farm with hillsides	0	0	1	10	0.5	8	1	10

4.3. Results

4.3.1 Income

The total net income optimized by the model did not vary very much in function of the soil cover constraints (Fig. 4.2) as differences were always less than 2 % between the 30 and the 95 % value for soil cover constraint. However, net income was strongly affected by the number of cows (from 0 to 12) and the milk market scenario (unlimited or limited milk volume marketable). Without dairy cows the total income for three years was around 1 500 kAr for the medium-sized farm with hillsides fields, 3 800 kAr for the medium-sized farm with irrigated paddy fields. The optimization was infeasible for the small-sized farm with hillsides fields with no cows. In the scenario with a limited milk market this income can be multiplied by 5 to 16, depending on farm type. It ceased to increase from 8 cows due to limited milk sales (Fig. 4.2 b, d, f). With more cows the cost of purchased forage was barely compensated by animal product sales (milk, manure). By contrast in the open market scenario the net income increased systematically with number of cows as there was no limitation to the quantity of milk that can be sold (Fig.4.2 a, c, e). In our study the net income could be multiplied by 8 to 23 when 12 cows were owned. The relative contribution to net income changed with animal selling becoming more important compared to income from crops products.

4.3.2 Selection of CA systems

After an optimization on three years it is possible to see where the model chose to select CA systems in function of the different scenarios. In our study only conventional systems were possible for irrigated paddy fields. The model chose CA systems for the whole area of poor water control paddy fields and alluvial soils, because CA was more productive in terms of grain and biomass and more flexible in terms of the cropping calendar (Appendix 3). Only for hillsides did the proportion of CA selected by the model vary according to the different parameters, such as the soil cover constraint (30 or 95 %) and the price of forage purchased from the market (Fig. 4.3). With 12 cows to feed and a forage market price of 0.15 kAr /kg, which is only 50 % more than the actual (2011) price in the Lake Alaotra region, it appears almost impossible to implement CA while maintaining more than 80 % of soil cover. Above a threshold forage price of 0.2 kAr/kg, it becomes cheaper to use biomass produced on the farm through CA than to purchase it from outside for all kinds of farm.

4.3.3 Proportion of purchased and produced on-farm forage

All three farms type were almost self sufficient in forage to feed up to 7 cows (Fig. 4.4) with only a limited necessity for purchased forage. In order to keep more cows the demand for purchased forage increased strongly as on-farm forage production cannot increase as it is limited by the land area available and the yield of the species used. In the limited market scenario with more than 7-8 cows the extra milk and manure sold hardly compensated the extra expense of forage (fig 4.2 b, d, f).

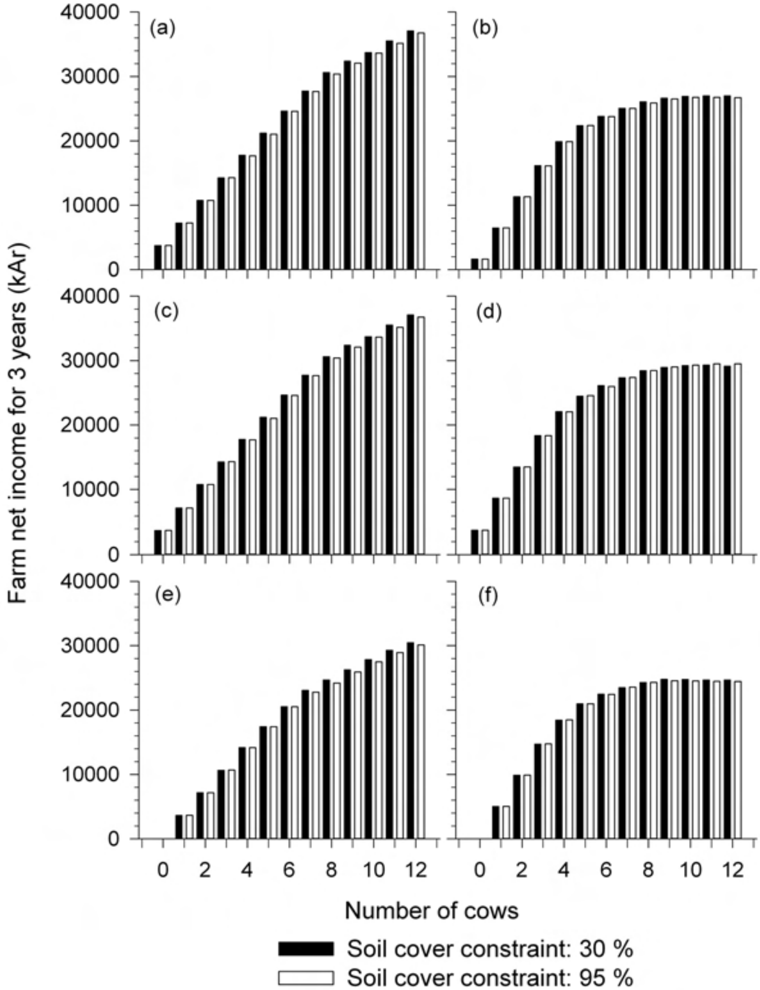

Figure 4.2. Total income over three years for three kinds of farm for three years: a,b medium-sized with hillsides, c,d medium-sized with irrigated paddy fields and e,f small-sized with hillsides fields as a function of an increasing number of cows from 0 to 12; and two degrees of soil cover (30 and 95 %, black and white bars respectively). Two scenarios of milk market are explored: a,c,e open or b,d,f limited milk market. When no values are given the solution is not feasible in the optimization process.

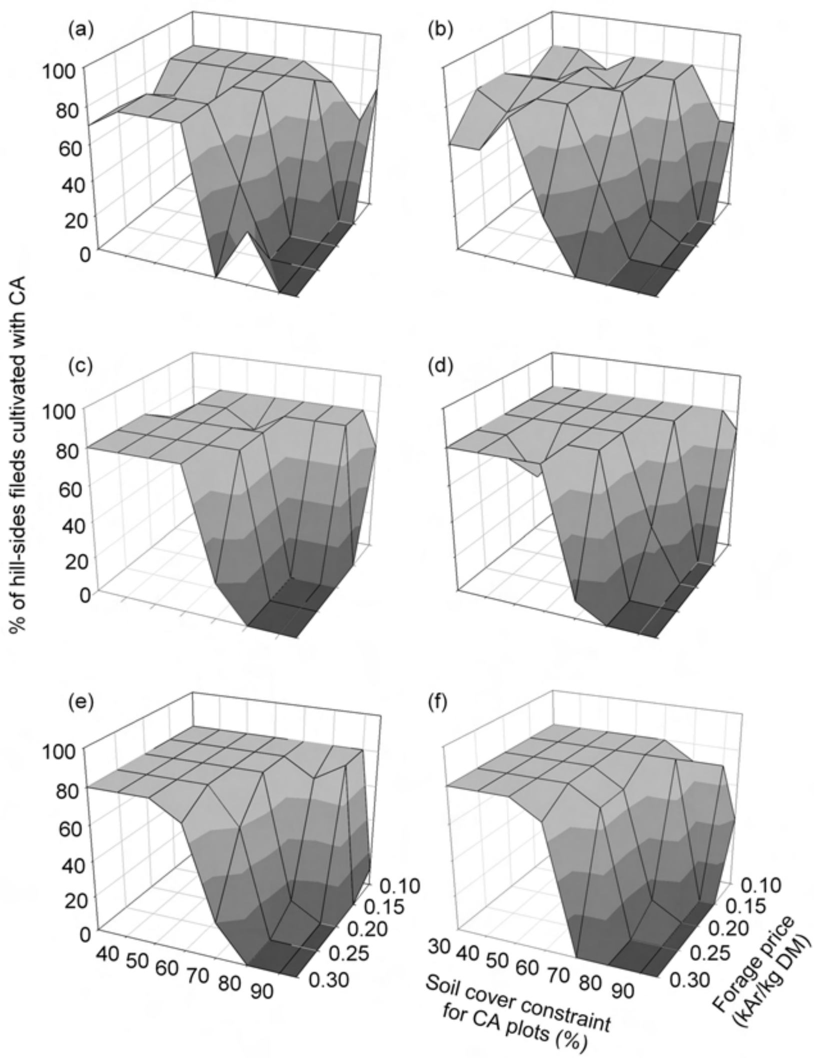

Figure 4.3. Percentage of hillsides fields covered by CA cropping systems, the third year: a,b medium-sized with hillsides, c,d medium-sized with irrigated paddy fields and e,f small-sized with hillsides fields as a function of an increasing constraint for soil cover of CA fields (30 to 95 %); forage. Two scenarios of milk market are explored: a,c,e open or b,d,f limited milk market. Simulations are made for farms with 12 cows.

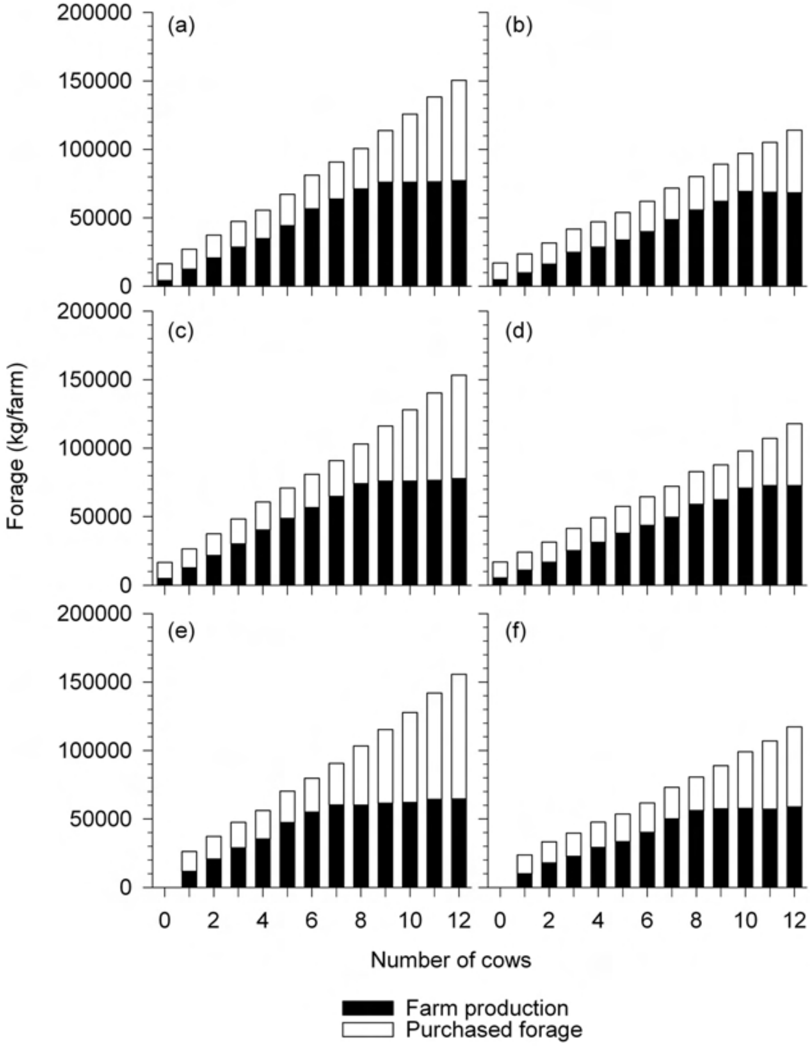

Figure 4.4. Forage origin, on farm produced or purchased from market for three years: a,b medium-sized with hillsides, c,d medium-sized with irrigated paddy fields and e,f small-sized with hillsides fields as a function of an increasing number of cows from 0 to 12. Two scenarios of milk market are explored: a,c,e open or b,d,f limited milk market. Soil cover constraint for CA plot has been set to 95 %. When no values are given the solution is not feasible.

4.3.4. Proportion of forage production coming from CA on hillsides

Fig. 4.5 shows the forage used by animals coming from hillsides. This forage is in addition to forage and crop residue coming from CA practiced on poor water control paddy fields and alluvial soil (data not show). The quantity of forage coming from hillsides varied among the three types of farm as the relative area of hillsides fields compare to other fields varies among these types of farm. The farm with more forage coming from the hillsides was the “medium-sized farm with hillsides” as such farms do not have paddy field to produce rice straw compared to the “medium-sized farm with irrigated paddy field” and more hillsides fields than for the type “small-sized farm with tanety”. For each scenario and farm type the threshold of 6-8 cows was observed to a significantly increase in biomass use as forage coming from the hillsides fields. Nevertheless the proportion of forage coming from CA was systematically smaller when the soil cover constraint was set to 95 % than when it was set to 30 %. In fact the model chose less CA when the soil cover constraint is too high (*i.e.* keeping 95 % of soil cover) as this threshold reduced strongly the quantity of biomass usable as forage. Thus, the model chose conventional crop production activities as they allowed all of the biomass to be removed from the field. When looking at scenarios with a soil cover constraint of 30 % for implementing CA, for all three kinds of farms, and in both market scenarios, CA started to be implemented with more than six cows. But in more constraining situations, *i.e.* when forcing 95 % of soil cover to be kept on the CA plot the model also chose to introduce CA but it was almost impossible to maintain CA fields with the increasing demand on forage (Fig. 4.5 a, c, e). In contrast it was easier to use biomass from CA fields when the pressure was less (Fig. 4.5 b, d, f) due to the cheaper forage available on the market.

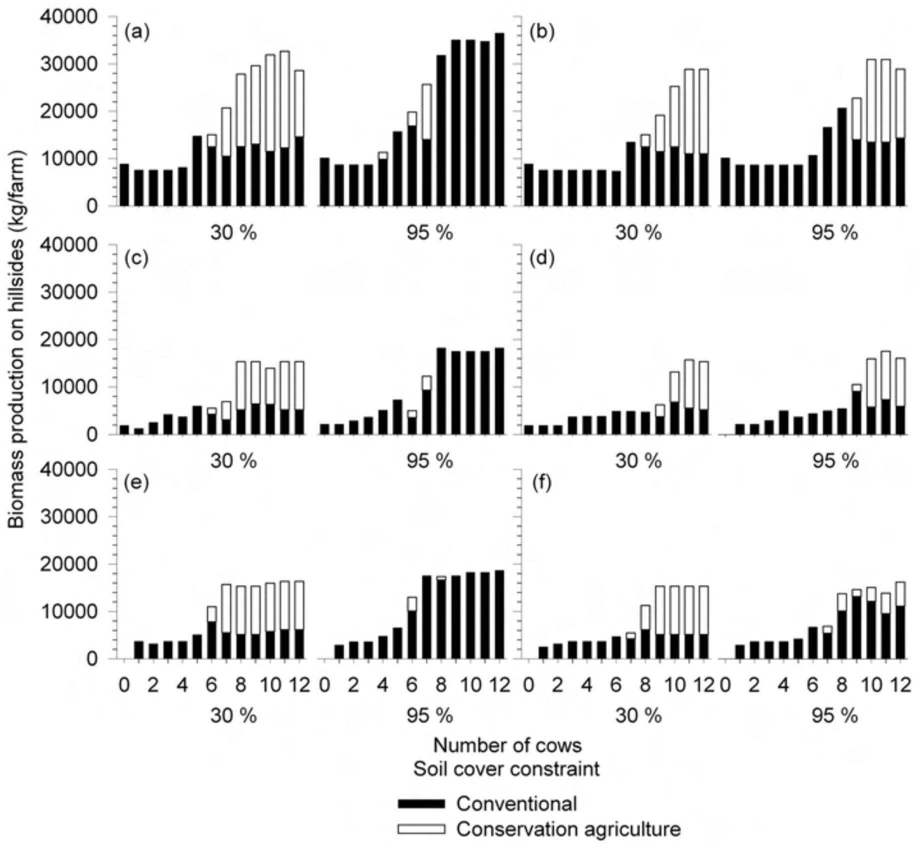

Figure 4.5: Quantity of forage produced on-farm on hillsides coming from conventional fields (blacks bars) or CA fields (white bars) for three years: a,b medium-sized with hillsides, c,d medium-sized with irrigated paddy fields and e,f small-sized with hillsides fields as a function of an increasing number of cows from 0 to 12; and two degrees of soil cover (30 and 95 %).Two scenarios of milk market are explored: a,c,e open or b,d,f limited milk market. When no values are given the solution is not feasible.

4.4. Discussion

When simulating two situations of milk market on three kind of farm we observed that changing the soil cover constraint had little impact on farm income, but influenced the proportion of CA fields on hillsides and the source of forage for cows.

4.4.1 Impacts of mulching or cattle feeding on farmers' income

Net income was strongly influenced by the characteristics of the milk market (Fig.4.2). In the case of a limited milk market, with high milk prices, it was more profitable to maintain the herd between one to six cows, even with less productive cows (local breed). On the contrary in an open milk market scenario with lower prices farm income is directly linked with the amount of milk and manure produced. It was not profitable to have more than seven cows when the milk market was limited. This situation illustrates well that when the market is well structured with the active presence of industrials and/or collectors, milk production is an efficient way to improve and stabilize the income of tropical small scale farmers (Bernard et al., 2010).

4.4.2 Soil cover and forage production

Fig. 4.3 suggests that it is impossible to maintain sufficient soil cover when the biomass is a scarce resource, *i.e.* when the forage prices are high. But it is still possible to keep at least 50 % of soil cover on 80 % of the hillsides fields in all entire situation we have simulated, even with 12 cows. This can have implications for a dissemination strategy. If the technical message spread is to keep soil entirely covered without allowing exporting part of the biomass from the field, especially in biomass scarcity situations, then farmers will probably choose not to use CA, not even in part of their hillsides lands. In fact, they will prefer not to retain even part of the biomass produced when there is an option of economic benefit from selling it. This situation is common in the

Vakinankaratra region of Madagascar (Kasprzyk, 2008) where milk is easily sold, forage is scarce and proportion of CA in famers fields close to zero. The proportion of forage purchased versus produced on farm changes with the growing demand of forage. In general the farm is able to produce all the forage to feed up to six/seven cows. This is true even if there is still a need for purchased forage to fill a gap during the dry season as there is no hay or other form of storage. In the case of a limited milk market the expense of feeding more than six/seven cows is not compensated by the milk and manure sales and the net income will reach a ceiling (Fig. 4.2 b, d, f). Thus, in case of a limited milk market, it is not economically interesting to own more than six cows. But twice as many cows also require twice as much capital and give twice as much manure production. With more than seven/nine cows, more forage is purchased from outside the farm, and the net nutrient balance of the farm improves due to the additional biomass import. Furthermore this fertility transfer can be seen as having ecological benefits at a broader farming system level as most of the forage is bought during the dry season and comes from the wet lowland area where there is still biomass production (Douhard, 2010). These areas, mainly around the Alaotra river and swamp, are areas where sediments are deposit from the erosion of the surrounding hills (Ferry et al., 2009). Thus organic manure produced by cows fed with this kind of forage and applied on fields, among them hillsides, is a means of recycling of nutrients at the watershed level. The question is whether it is more interesting for the farmers, both economically and environmentally, to increase their herd above six cows with other dairy cows or to switch to increase the number of Zebu. When trying to produce more forage – having above six/seven cows – the model chose to introduce CA cropping systems producing forage on the hillsides (Fig. 4.5). Thus in this case CA is compatible with cattle raising as a potential way to increase biomass/forage production. But in a more constraining situation (*i.e*. open milk market, with a strong demand on forage and pressure on biomass) it is almost impossible to implement CA on hillsides while keeping 95 % of soil cover. The simulations also showed that it is impossible to implement CA without using part of the biomass to feed cattle in a context of a growing market for milk. In that case all of the agroecological functions of mulch cannot be fulfilled. Regarding physical effects such as erosion control or water balance improvement, partial cover can be sufficient under tropical climate conditions (Findeling et al., 2003; Mulumba and Lal, 2008). But partial biomass export to feed cattle is incompatible with weed control or restoration of soil functions under CA. Therefore, the allocation of biomass to soil covering or cattle depends on the farmer’s objectives, constraints and priorities (Erenstein, 2011; Valbuena et al., 2012).

4.4.3 The GANESH modelling approach

The GANESH model was created using the available knowledge on cropping systems performance in farmers’ conditions, farm and cattle characteristics in the Lake Alaotra region. In the future GANESH model could be used to test scenarios based on new hypothesis. Some aspects can be improved at four levels: the cropping system, animal production, farmer behavior and regional level. First, at cropping system level, the model does not take into account mid-term effects of CA on soil fertility and weeds pressure and their consequences for crop productivity. To analyze longer rotation periods then a means of incorporating the impacts on crop yields with years of practicing CA is needed. But, to date, the long term bio-physical effects of CA have not been clearly characterized in the Alaotra situation (Penot et al., 2011). Regarding weeds, we only take into account a quantity of labor for weeding that increases linearly with the decreasing rate of soil cover, although in practice the relationship is more complex as weed pressure does not vary linearly with soil cover (Teasdale and Mohler, 2000) and the labor needs are perhaps also not linearly related to weed pressure. In addition in GANESH, weeds are constrained to be completely controlled by farmers using a certain amount of labor to do so. If insufficient labor is available in a farm then the model will search for other crop production activities more compatible with farm constraints. The model can be improved by introducing the possibility to have only a partial, or a late, control of weeds having consequences on crop production (Jourdain et al., 2001) which could be more realistic. Further, neither the link between nutrient exports from field through biomass, nor the soil erosion impact on future crop yields are included in the model. Introducing these relationships could push the model outcomes to keep more biomass on field and then purchase more forage. Secondly, GANESH does not alter animal production as a function of the feeding regime. Milk production of cows is calculated according to their genetic potential (local and improved dairy cow breeds) and the month of lactation (following the theoretical optimal milking curve). The milk production level remains constant throughout the whole simulation period because we assume that the energy supplied by the feed always cover all of the cows 'requirements for milk production. To improve the model accuracy, a mathematical function could be designed to allow dynamic changes in milk production, according to forage availability and quality (León-Velarde, 1991; León-Velarde et al., 2003). The impacts on model outputs of introduction of such changes are difficult to anticipate as GANESH will optimize the crops choices, the level of animal feeding and the milk production. However, introducing such improvements will be important in order to design a functional decision support system to advice farmers. Thirdly, GANESH gives the optimum economical and technical solution. When the optimum solution includes CA, the model can suggest a complete shift from conventional to CA or inversely from one year to another. In practice, farmers usually cannot shift between such different systems such rapidly. Farmers' aversion to risk makes them more cautious with new technology adoption (Barbier, 1998; Pannell et al., 2000). A way to take into account for this aspect in the model could be to constrain the proportion of new area in CA from one year to another. Fourthly, GANESH models individual farms. To simulate adoption of CA at regional level then the competition between farms to biomass access should be taken into account. Up to now such competition is accounted for only through the price of forage. Implementing such a change may cause the model to favor on-farm biomass production by choosing more CA systems which produce more biomass than conventional ones.

4.4.4 Similar studies

We have seen that CA and milk production can be compatible and in some cases mutually profitable. Few other studies deal with the relationship between CA and cattle raising and in general they are driven by the local context of CA and cattle production. In Brazil more papers focus on technical issues. Landers (2007) presents examples of how to establish forage associated with a crop or how to establish crops in pastures. In Africa, most of the references stress the *a priori* difficulty to do CA, mainly because of a competition for biomass (Erenstein, 2003; Giller et al., 2009); or propose “CA” systems which do not fit totally with accepted (FAO) definition of CA (Lahmar et al., 2011; FAO, 2012a). In Southeast Asia many studies have investigated the rice-wheat systems in the Indo-Gangetic Plains (Erenstein et al., 2008, 2009; Erenstein, 2010). Erenstein et al (2009) confirm that it is possible, and necessary, to use part of crop residues to feed cattle in these systems. In Mexico (Limon-Ortega et al., 2006) showed a soil characteristics improvement positively linked with the quantity of residue retained. But the difference in term of cereal grain yield appeared only when comparing with or with mulch but not when comparing different level of residue retention, same results were reported by Govaerts et al. (2005). Fisher and Tozer (2012) provided a comprehensive overview of mixed farming systems including sheep and CA in Australia. In the end the relative importance of livestock or cropping system depends on the farmer’s preference, land capability and of course the economic benefits accrued. Lilley and Moore (2009) compared various residues management and grazing methods on soil cover, animal productivity and farm income in Australia. They conclude that “*Maintaining a constant stocking rate […] using a cover threshold of 70%, […] caused minimal reduction in gross margin. Stubble retention resulted in a win-win at most sites, with 4–8% increase in the proportion of time when cover was above 70% and generally a small increase in crop yield or gross margin*”. To our knowledge, theirs is the only study that examines the balance between soil cover in direct seeded systems, with animal production and farm income. Despite the very different environment, their value of 70 % is close to the value of 50 % of soil cover kept on hillsides even with 12 cows we found in Madagascar.

4.5. Conclusion

By using data from fields' surveys in a farm model we could explore some facets of integration of CA at farm level on small farms in the Alaotra lake in Madagascar. Setting a more or less strong constraint on the degree of soil cover to be retained on CA plots did not significantly modify the total farm net income. It was possible to maintain > 50 % of cover on hillsides for CA fields even on a farm with twelve cows. By contrast, it was impossible to keep 95 % of soil cover on these fields due to the great demand for biomass and the high price of forage. If there is less demand for crop residues, CA is a technically and economically interesting solution to increase biomass production. In conclusion, we find that CA and livestock can be compatible and even mutually beneficial. Even when there is a strong biomass demand for fodder it could be more profitable to practice CA on some fields and to purchase forage to compensate the biomass retention in the field. CA and livestock are mutually beneficial when the pressure on biomass is less intense. In this case, CA can be an efficient way to increase forage production at farm level while maintaining the major agroecological functions of mulch. Our study is the first, to our knowledge, that models the impact of practicing CA, with various degrees of biomass export, on integration with livestock and farm income for smallholders. Optimization was a useful method as it allows exploration among millions of combination of potential production systems that represent the numerous constraints and goals of the farm. It further allowed an objective comparison of the production activities, based on quantitative data and taking into account the complexity of the interactions between theses production activities at farm level. This kind of *ex ante* study can be useful for guiding a CA design approach to explore impacts of a possible change in the context (inputs, forage, workforce, crop animal products prices); to understand which changes and trade-offs are associated with CA systems at farm level and which types of CA systems are more suitable for different types of farm.

Chapter 5

PRACT (Prototyping Rotation and Association with Cover crop and no Till) – a tool for designing Conservation Agriculture systems

This Chapter is to be submitted for publication as:
Naudin, K., Husson, O., Scopel, E., Auzoux, S., Giner, S., Giller, K. E. 2012. PRACT (Prototyping Rotation and Association with Cover crop and no Till) – a tool for designing Conservation Agriculture systems

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Abstract

Moving from conventional to CA implies deep changes in the organization of cropping systems. We propose a method for formalizing the process of CA cropping system design using a tool called PRACT (Prototyping Rotation and Association with Cover crop and no Till) applied to a Malagasy case study. The input information for PRACT concerns: i) crop adaptation to biophysical conditions, ii) cover crop adaptation to biophysical conditions, iii) agroecological functions of cover crop, iv) crop production, v) association possibilities between crop and cover crop, and vi) agroecological functions of the cropping system. All the information was derived from expert knowledge developed over more than 12 years of agronomic experiments in Madagascar. The output from PRACT is a list of cropping systems, i.e. crop and cover crop associations and their sequences over three years. These cropping systems are characterized by their potential agroecological functions and crop production. The PRACT model selects a list of cropping systems taking into account the above information by using elaborate rules governing the intercropping and sequences between crops and cover crops. Examples of the outcomes of model simulations are provided for four different kinds of field. Taking into account the range of potential crops and cover crops, the number of cropping systems that was theoretically possible for the different field types ranged from 19,683 to 2.98×10^{13}. PRACT reduced this number by a factor of up to 28 times to propose possible cropping systems. Cropping systems are first selected in terms of the biophysical requirements of plants, plant compatibility and agronomic rules. But they are not all suitable for every kind of farmer. Thus by using PRACT output, a second cropping system selection step can be taken based on these cropping system characteristics, i.e. crop production and agroecological functions. By doing so the number of cropping systems selected can reach a reasonable value that can be handled by technicians and farmers. Lastly, possible uses and further development of the tool are discussed.

5.1. Introduction

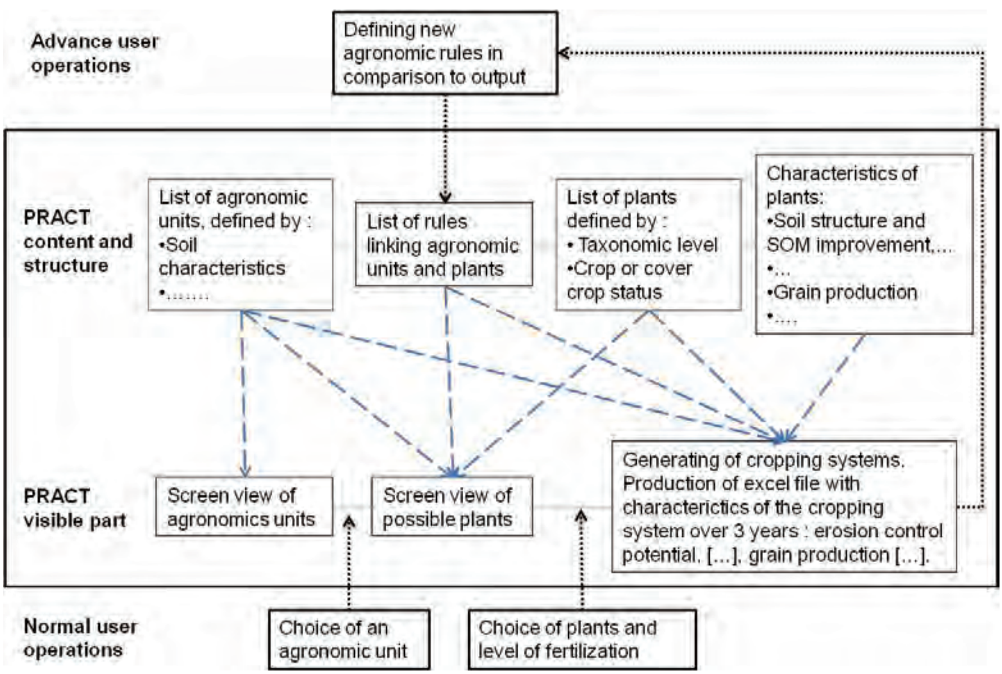
Crop sequences and/or intercrops are one of the three central pillars of Conservation Agriculture (CA) (FAO, 2012a; Sayre and Govaerts, 2012). Moving from conventional to CA implies deep changes in the organization of cropping systems, yet the agronomic and technical rules to support such changes have rarely been formalized. Manuals have been developed that present CA technical management and the underlying rationale in terms of crop and soil functioning (ACT, 2005; Husson et al., 2009; Seguy et al., 2012). But no tools are available to support the design of appropriate rotations for CA systems involving cover crops, such as have been developed for conventional crop rotations, e.g. ROTAT (Dogliotti et al., 2003) and ROTOR (Bachinger and Zander, 2007). These tools combine several crops to generate rotations. Filters limit the full factorial number of possible crop rotations. These filters are based on expert knowledge and enable the exclusion of crop successions that are not feasible or not advisable.

In this paper, we propose a way of formalizing the process of CA cropping system design. To that end, we formalized the underlying hypothesis behind the design, based on field characterization, crops and cover crop adaptation to different field types, crop and cover crop agroecological functions, the possible intercrop combinations and sequences of crops and cover crops. We illustrate this reasoning through the design and use of a tool called PRACT (Prototyping Rotation and Association with Cover crop and no Till) applied to a Malagasy case study. This approach can be used to propose a list of possible cropping systems for testing in the field or *in silico* at both field and farm level.

5.2. The PRACT tool (Prototyping Rotation and Association with Cover crop and no Till)

We identified six different kinds of information that can support the design of new CA cropping systems: i) crop adaptation to biophysical conditions, ii) cover crop adaptation to biophysical conditions, iii) agroecological functions of cover crops, iv) crop production, v) compatibility for intercropping of crops and cover crops, and vi) agroecological functions of the overall cropping system. In PRACT this information is organized in a knowledge database including data on crops, cover crops, agronomic units, and the relationships between these three components (Fig. 5.1). The underlying expert knowledge had been developed since the 1990s in Madagascar and other tropical countries by a team of CIRAD agronomists and their local colleagues (Seguy et al., 2012) The expert knowledge was already formalized in technical manuals (Husson et al., 2009, 2012). PRACT allows the user to generate crop rotations based on CA principles for a defined agro-climatic context that are best adapted to cope with local constraints. It has been developed with the database management system Microsoft Access 2007® to make it accessible for potential users in developing countries.

Figure 5.2. Simplified plan of information processing in PRACT, interactions with the user and output.



5.2.1 Tool development

PRACT is organized (Fig. 5.1) around a database with 28 plants which are crops, cover crops, or both, suited to the Lake Alaotra region of Madagascar: *Arachis hypogaea, Arachis pintoï, Arachis repens*, *Avena sativa, Brachiaria brizantha, Brachiaria ruziziensis, Cajanus cajan, Crotalaria grahamiana, Crotalaria juncea, Crotalaria spectabilis, Dolichos lablab, Eleusine coracana, Glycine max, Ipomoea batatas, Lolium multiflorum, Manihot esculenta, Mucuna pruriens, Oryza sativa, Pennisetum clandestinum, Phaseolus vulgaris, Solanum tuberosum, Sorghum bicolor, Stylosanthes guianensis, Vicia villosa, Vigna subterranea, Vigna umbellata, Vigna unguiculata, Zea mays.* The plants are characterized according to their ability to be grown in different environments, here defined as agronomic units, a corpus of “rules” that specify the place each plant can have in intercrop associations or crop sequences, and their potential efficiency in fulfilling agroecological functions and characteristics such as “simplicity of management” or “ability to produce during marginal periods” (Tab. 5.1).

The final output of PRACT is a list of cropping systems, i.e. crop and cover crop intercropping in the cropping season and in the off-season over a three year period. Each of the cropping systems is characterized by the same factors as the plants (Tab. 5.1). The characterization of cropping systems is calculated by summing up the characteristics value of each plant in the cropping system. Even after applying filters, the number of possible cropping systems can be too large to be handled by technicians or farmers. Thus, a further step is to select from among these cropping systems those that fit in with farmers’ particular goals and constraints. Selection can be based on characterization of the agroecological function, or ease of implementation, or the species of crop and cover crop chosen by the farmer. The number of cropping systems can also be reduced beforehand, during the PRACT cropping system generation process, by selecting only some of the crops and cover crops based on farmers’ preferences. But reducing *a priori* the number of crops and cover crops will reduce the chances of identifying an innovative cropping system. We thus propose that PRACT should be used in two steps: first obtain a list of possible cropping systems based on the local conditions and general agronomic rules; and secondly choose from these systems those which fit in with farmers' main goals and constraints for both crop and animal production.

5.2.2 Plant characteristics

Plants (crop and cover crop species) are characterized by their outputs (grain production, tuber/root production, and biomass/forage production) and qualitative impacts on agroecological functions. Both are translated into semi-quantitative indicators (Tab. 5.1). All these indicators are based on expert knowledge (Husson et al., 2009).

Table 5.1. Characteristics and agroecological functions of crops and cover crops in the PRACT database.

	SOM increase and soil decompaction	Erosion control	N fixation	Nutrient recycling	Biomass production	Ability to produce during marginal periods	Weed control	Pest control	Ease of use
Crops									
Oryza sativa	-1	-1	-1	0	1	-1	-1	-1	0
Zea mays	1	0	-1	1	2	-1	0	-1	1
Sorghum bicolor	2	0	-1	2	2	-1	0	-1	1
Glycine max	-1	0	1	0	0	-1	-1	0	0
Arachis hypogaea	-1	0	1	0	0	0	-1	0	0
Phaseolus vulgaris	-1	0	1	0	0	1	0	0	0
Vigna subterranean	0	0	1	0	0	0	0	0	0
Vigna unguiculata	1	1	1	0	1	1	1	0	2
Vigna umbellata	1	1	1	0	1	1	1	0	1
Dolichos lablab	1	1	1	1	1	2	1	0	1
Vegetable	-1	0	0	0	0	1	-1	-1	0
Solanum tuberosum	0	0	-1	0	0	1	-1	-1	0
Mahinot esculenta	0	-1	-1	0	0	1	-1	0	1
Ipomoea batatas	0	1	-1	0	0	1	0	0	1
Cover crops									
Arachis pintoï	2	2	2	1	1	1	2	0	-1
Arachis repens	2	2	2	1	1	1	2	0	-1
Avena sativa	1	1	0	2	1	2	2	0	2
Brachiaria brizantha	2	2	0	2	2	1	0	0	0
Brachiaria ruziziensis	2	2	0	2	2	1	0	0	0
Cajanus cajan	1	0	2	1	1	1	1	0	0
Crotalaria juncea	1	0	2	1	1	1	1	0	1
Crotalaria grahamiana	1	0	2	1	1	1	1	0	1
Crotalaria spectabilis	1	0	2	1	1	1	1	0	1
Eleusine coracana	2	2	1	1	2	0	1	0	1
Lolium multiflorum	1	2	-1	1	2	1	1	0	0
Mucuna pruriens	0	1	1	1	1	0	1	0	0
Pennisetum clandestinum	2	2	0	2	2	1	0	0	0
Stylosanthes guianensis	2	2	2	2	2	1	2	0	2
Vicia villosa	1	2	2	2	1	2	2	2	1

5.2.3 Agronomic units

Agronomic units are defined as areas which provide uniform biophysical conditions that impact plants and cropping systems. Therefore a different set of cropping systems can be selected for each agronomic unit. For Lake Alaotra in Madagascar each of the 17 agronomic units is discriminated by: i) the position in the toposequence, ii) soil fertility and compaction, iii) the drainage or water logging status, iv) potential for irrigation management, v) the possibility or not of supporting the growth of an off-season cover crop (Fig 5.2, Fig. 5.3, Husson et al. 2012).

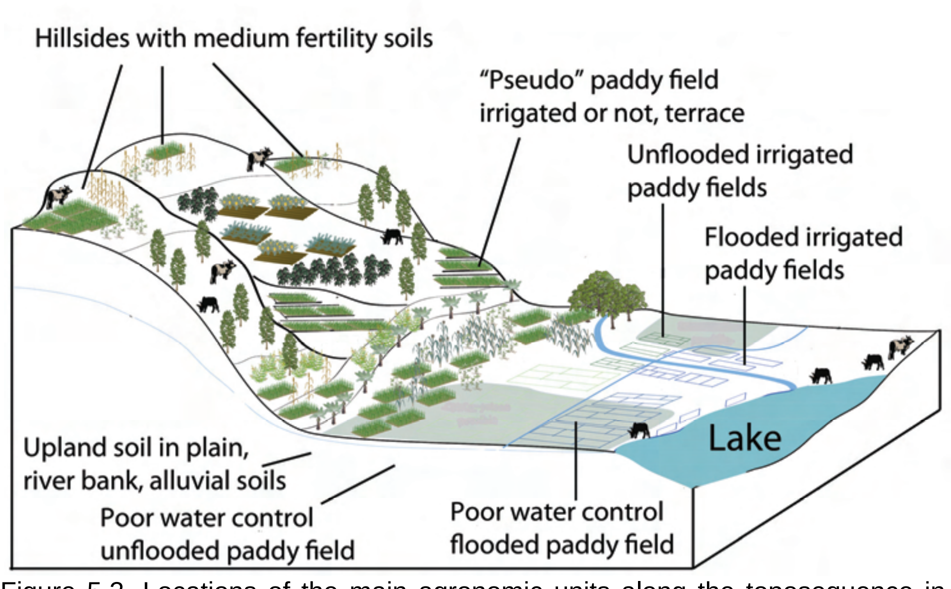


Figure 5.2. Locations of the main agronomic units along the toposequence in the Lake Alaotra region, adapted from Husson et al. (2012).

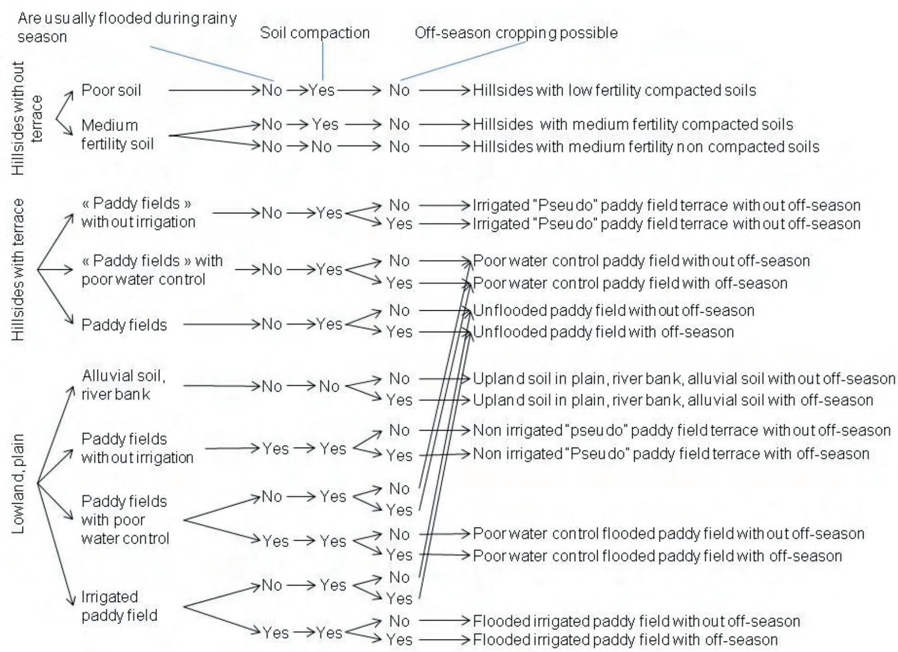


Figure 5.3. Decision tree to select the type of agronomic units in the lake Alaotra region as a function of the position in the toposequence, risk of flooding, soil compaction and possible off-season cropping due to the presence of a ground water table, adapted from Husson et al. (2012).

5.2.4 Agronomic rules

Plant species are also characterized by three kinds of constraints: i) whether or not plants can be grown on the different agronomic units, ii) whether or not the plants can be intercropped or grown in sequence, iii) more elaborate rules regarding plant associations and successions. The constraints are applied in three sequential steps in the cropping design process. The first step is the compatibility of plants and the agronomic units. It is determined with regard to each plant's requirements in terms of soil and the water regime. Soil is considered in terms of compaction and fertility. The water regime during the rainy season is driven by drainage and irrigation. Drainage is mainly determined by the position in the toposequence. Three types of water supply were identified: strictly rainfed fields, fields irrigated from channels only in the event of sufficient rainfall, or fields irrigated from channels with a secure access to water throughout the cycle (coming from a dam or a permanent source). During the dry off-season no fields can be irrigated and the only water source for crops and cover crops is capillary rise. The second constraint applied is to determine compatibility between crops and cover crops for intercropping. The possibility of associating plants results mainly from potential competition for light, water and/or nutrients. Table 5.2 lists crops and cover crops which can or cannot be intercropped together.

Table 5.2. Possibilities for intercropping (Y) or not (N) between crops and cover crops as given in the PRACT database.

	Arachis pintoï	*Arachis repens*	*Avena sativa*	*Brachiaria brizantha*	*Brachiaria ruziziensis*	*Cajanus cajan*	*Crotalaria grahamiana*	*Crotalaria juncea*	*Crotalaria spectabilis*	*Cynodon dactylon*	*Dolichos lablab*	*Eleusine coracana*	*Lolium multiflorum*	*Mucuna pruriens*	*Pennisetum clandestinum*	*Stylosanthes guianensis*	*Vicia villosa*	*Vigna unguiculata*
Arachis hypogaea	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	N	Y	Y	Y	N
Vegetable	N	N	Y	N	N	Y	Y	Y	Y	N	N	Y	N	N	N	Y	Y	N
Glycine max	N	N	Y	Y	Y	N	N	N	N	Y	N	Y	Y	N	Y	Y	Y	N
Manihot esculenta	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	N	Y	Y	Y	Y
Ipomoea batatas	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	N
Oryza sativa	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	N
Phaseolus vulgaris	N	N	Y	Y	Y	N	N	N	N	Y	N	Y	Y	N	N	Y	Y	N
Solanum tuberosum	N	N	Y	N	N	N	N	N	N	N	N	Y	Y	N	Y	Y	Y	N
Sorghum bicolor	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Vigna subterranea	N	N	Y	N	N	Y	Y	Y	Y	N	N	Y	N	N	N	Y	Y	N
Vigna umbellata	N	N	Y	N	N	N	N	N	N	N	N	Y	N	N	N	Y	Y	N
Vigna unguiculata	N	N	Y	N	N	N	N	N	N	N	N	Y	N	N	N	Y	Y	N
Zea Mays	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

The third step uses more elaborate rules about the crop sequences which are defined for each agronomic unit in PRACT. Below we describe how six groups of rules are defined for specific agronomic units of the Alaotra Region, but these are generic rules which can be applied to similar locations elsewhere.

Rule 1: if a cover crop is grown in the rainy season in Year *n* then the same cover crop should continue to be grown in the off-season of the same Year *n*. This rule applies for all perennial cover crops for all agronomics units. It also applies for annual cover crops except on agronomic units where off-season cultivation is possible, i.e.: *"irrigated paddy field terrace with off-season, poor water control paddy field with off-season, unflooded paddy field with off-season, upland soil in plain, river bank, alluvial soil with off-season, non-irrigated 'pseudo' paddy field, terrace with off-season, poor water control flooded paddy field with off-season, irrigated flooded paddy field with off-season"*. Perennial cover crops need to be grown for more than one season to produce a sufficient amount of biomass to justify their planting. When no off-season crop is possible the cover crop grown in the rainy season usually continues to grow for some weeks at the beginning of the dry season (*e.g., Crotalaria* sp., *C. Cajan* or *D. lablab* on *upland soil in plains, river banks, alluvial soil with off-season crops and cover crops*).

Rule 2: if cover crop *X* is grown in the rainy season of year *n* then the cover crop will also be *X* in the off-season of Year *n*, the rainy season of Year *n*+1 and the off-season of Year *n*+1. This rule applies for the following perennial cover crops that all take a long time to become established and produce sufficient biomass: *A. pintoï, A. repens, B. brizantha, B. ruziziensis, P. clandestinum, and S. guianensis.* This rule also applies for all agronomic units where these plants can be grown. *A. pintoï* or *A. repens* can be used as "living mulch" and are difficult to kill completely. For these reasons it makes no sense to kill them one or two years after installation. In general *B. brizantha, B. ruziziensis* and *P. clandestinum* are used as forage by farmers who do not return the fields rapidly to annual crops (Andriarimalala et al., 2012) . In general, on hillsides, *S. guianensis* does not produce sufficient biomass to be killed and used as dead mulch until at least three years after sowing (Chapter 3, Naudin et al., 2011).

Rule 3: if the cover crop in the off-season of Year *n* is *A. pintoï, A. repens, or S. guianensis,* then the crop in Year *n*+1 should not be a legume such as *A.*

hypogaea, G. max, P. vulgaris, V. subterranea or *V. unguiculata*. This rule concerns only perennial cover crops. This rule applies for all agronomic units where these cover crops can be cultivated. *A. pintoï* and *A. repens* are difficult to install so it is more logical to grow a cereal in succession to make full use of the N input from the cover crop. There is also more risk of soil borne pathogens if legumes are intercropped or introduced in the crop sequence.

Rule 4: if the cover crop in the off-season of Year *n* is *A. pintoï, A. repens, or S. guianensis* then the crop in Year *n*+1 should not be *I. batatas* or *S. tuberosum.* This rule concerns only perennial cover crops. This rule applies for all agronomic units where these cover crops can be cultivated. The justification is possible above- or below-ground competition between the crops and cover crops.

Rule 5. if the cover crop in the off-season of Year *n* is *B. brizantha, B. ruziziensis, P. clandestinum,* then the crop in Year *n*+1 can only be *M. esculenta* and no crop can be grown in Year *n*+2. This rule concerns only perennial cover crops. Cassava can be intercropped with *Brachiaria* spp. without loss of yield (Charpentier et al., 2005).

Rule 6: sufficient biomass should be produced in Year *n*, or in the off-season of Year *n* to be able to grow using CA in Year *n*+1, e.g. plants that produce enough biomass are species such as *A. pintoï, A. repens, A. sativa, B. brizantha, B. ruziziensis, C. cajan, C. grahamiana, C. juncea, C. spectabilis, D. lablab, E. coracana, L. multiflorum, M. pruriens, P. clandestinum, S. bicolor S. guianensis*, *V. umbellata, V. unguiculata, V. villosa,* or *Z. mays.* This rule concerns both annual and perennial cover crops.

5.3. Application of the PRACT tool

We illustrate here the output of PRACT for four contrasting situations in the Alaotra region (Fig. 5.4):

- Hillsides with low fertility compacted soils
- Hillsides with medium fertility non-compacted soils
- Unflooded paddy field with off-season crops and cover crops

- Upland soil in a plain, river banks, or alluvial soil with off-season crops and cover crops

The crops and cover crops taken into consideration in these simulations are listed in Table 5.3.

For each of the simulations we followed two steps. Firstly we calculated the number of possible cropping systems taking into account biophysical constraints and agronomic rules. Secondly we presented a sample selection of a subset based on the supposed average farmer preferences in the Alaotra region. This last step was closely linked with the type of farmer, i.e. for the same type of field, farmers may not perceive biophysical constraints in the same way and will not give the same priority to the various agroecological functions.

5.3.1 Hillsides with low fertility compacted soils

As three crops and nine cover crops can be grown on this soil (Tab. 5.3), the factorial combination gave 19,683 possible combinations without taking into account plant species incompatibility and agronomic rules. After applying the rules, the number of cropping systems could be reduced to 5,501. Among them several combinations were similar, for example *Brachiaria* spp. and *P. clandestinum* are subject to the same kind of rules and have the same impact on the crops (Table 5.1). The same applies for *C. grahamiana, C. spectabilis* and *C. juncea*, except for differences between them in palatability for cattle (Husson et al., 2009). Thus, if we aggregated together similar plants, the total number of cropping systems was reduced to 1,031. These were the possible cropping systems, but we could select a subset from them taking into account farmer preferences or *in situ* constraints, see below.

In fact, the main justification for CA on these types of soil is to improve soil quality and thus to open up new possibilities in terms of cropping. Thus, when sorting according to the capacity to increase SOM and improve soil structure and limit erosion, the systems selected were those with sorghum associated with legume cover crops. The best cropping systems had sorghum associated with *S. guianensis* in the first two years and *S. guianensis* alone for the last year. But sorghum is not consumed in this area. Thus, to select a system producing food, only those with cassava could be selected. The best cropping systems that combined cassava production, SOM improvement and erosion control were: *M. esculenta* + *S. guianensis* in year 1 and 2, and *S. guianensis* alone in year 3, or *M. esculenta* + *Brachiaria* sp. in year 1 and 2 and *Brachiaria* sp. alone in year 3.

Figure 5.4. Representation of the reduction in the number of cropping systems (crop intercrops and successions over 3 years) from all the possible combinations to fewer cropping systems that address specific goals.

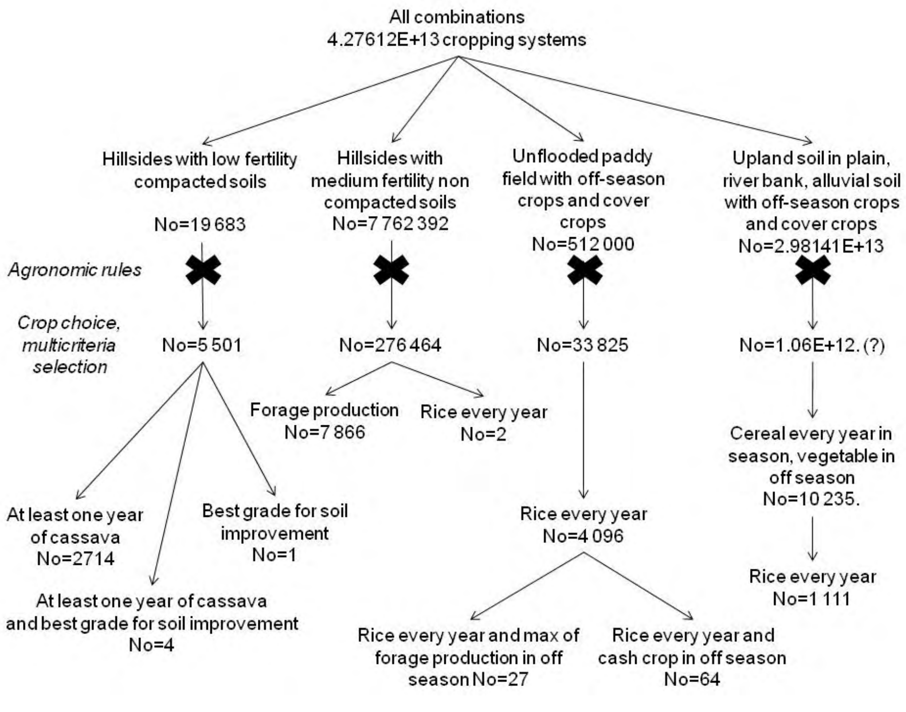


Table 5.3: List of plants which can be grown for the four simulated agronomic units.

	Hillsides with low fertility compacted soils	Hillsides with medium fertility non compacted soils	Unflooded paddy field with off-season crops and cover crops		Upland soil in plain, river bank, or alluvial soil with off-season crops and cover crops	
	Season	Season	Season	Off-season	Season	Off-season
Arachis pintoï		X			X	X
Arachis repens		X			X	X
Avena sativa		X		X	X	X
Brachiaria brizantha	X	X			X	X
Brachiaria humidicola			X	X	X	X
Brachiaria ruziziensis	X	X			X	X
Cajanus cajan		X			X	X
Crotalaria grahamiana	X	X			X	X
Crotalaria juncea	X	X			X	X
Crotalaria spectabilis	X	X			X	X
Dolichos lablab	X	X		X	X	X
Eleusine coracana		X			X	
Lolium multiflorum		X		X	X	X
Mucuna pruriens		X			X	X
Pennisetum clandestinum	X	X			X	X
Stylosanthes guianensis	X	X			X	X
Vicia villosa				X		X
Vigna umbellata		X			X	
Vigna unguiculata		X			X	
No cover crop	X	X	X	X	X	X
Total number	9	18	2	6	19	17
Arachis hypogaea		X			X	
Glycine max					X	
Ipomoea batatas		X			X	X
Manihot esculenta	X	X			X	X
Oryza sativa		X	X		X	
Phaseolus vulgaris		X		X	X	X
Solanum tuberosum						X
Sorghum bicolor	X	X		X	X	X
Vegetable				X		X
Vigna subterranea		X			X	
Vigna umbellata		X			X	
Vigna unguiculata		X			X	X
Zea Mays		X			X	
No crop	X	X	X	X	X	X
Total number	3	11	2	4	12	8

5.3.2 Hillsides with medium fertility, non-compacted soils

As 11 crops and 18 cover crops can be grown (Tab. 5.3), the factorial combination gave 7,762,392 possible combinations without taking into account plant incompatibility and agronomic rules. After applying the rules, the number of cropping systems could be reduced to 276,464. These were the possible cropping systems, but we could select a subset from among them taking into account farmer preferences.

For example, when searching for systems with the maximum number of rice crops, i.e. in years 1, 2 and 3, only 2 cropping systems were possible: rice with *A. pintoï* and *A. repens* living cover. Other cover crops were too competitive because of their rooting systems (grasses) or above-ground biomass production (other legumes) to be associated with rice. But these two cropping systems were among the eight worst in terms of ease of cropping system implementation. When searching for cropping systems with the maximum quantity of forage produced, i.e. either, *A. sativa, B. brizantha, B. ruziziensis, L. multiflorum*, *P. clandestinum, or* S. *guianensis* in years 1, 2 or 3, 132,301 cropping systems were possible. With the same plants used each year, 7,866 cropping systems were possible. The best systems in terms of erosion control and SOM improvement numbered 76. They included *A. pintoï*, *B. brizantha*, *B. ruziziensis*, *E. coracana*, *V. umbellata*, *V. unguiculata, V. subterranea, S. bicolor or S. guianensis*. Further selection should be made according to farmer preferences and complementarity with other fields on the farm.

5.3.3 Unflooded paddy field with off-season

One crop (*O. sativa*) and one cover crop (*B. humidicola*) can be grown in season and five crops, or three cover crops can be grown during the off-season (Tab. 5.3). The factorial calculation gave 2×2×5×4 = 512,000 possible combinations taking into account that only four cover crops in the off-season were considered, as *B. humidicola* can only be grown in the off-season when it is grown in the rainy season, and that it is also possible to have no crop or no cover crop in the cropping season and the off season. After applying the rules, the number of cropping systems could be reduced to 33,825 combinations. Within this list we could select a subset of cropping systems considering that farmers want to produce rice each year in this kind of field. Then the number of possible cropping systems was further reduced to 4,096. Furthermore, if we considered that because these soils are fertile, with water available, and represent only a small area, farmers want to produce cash crops during the off-season (i.e. vegetables and *P. vulgaris*), then the number of possible cropping systems became 64. These systems are based on sequences between rice and vegetables or *P. vulgaris.* Vegetables and *P. vulgaris* can be associated with *A. sativa or V. villosa.* If the famer wants to produce rice every year and produce as much forage as possible in the off-season then he/she will associate off-season crops with forage cover crops. Then 27 cropping systems are possible based on a succession between rice and *A. sativa*, *V. villosa* or *L. multiflorum*. Those with *V. villosa* each year may increase soil N content even when all the above-ground biomass is removed (Rochester and Peoples, 2005; Anugroho et al., 2009).

5.3.4 Upland soil in a plain, river banks with alluvial soil and off-season cover crops

As 19 crops and 12 cover crops can be grown in the cropping season and 17 crops and 8 cover crops in the off-season (Tab. 5.3), there were 2.98141×10^{13} possible combinations. With this huge number of combinations, it was impossible to run PRACT with all the plants to find the number of possible cropping systems. For non-compacted hillside soils, the number of cropping systems was reduced to 6.6% of the original number after applying the rules. If we used this same coefficient, the number of cropping systems remaining was still 1.06×10^{12}. But we were able to further reduce the choice by taking into account that these types of fields are rare and the area per farm small so that farmers wish to produce as many crops as possible. Farmers will grow a cereal crop each rainy season and a cash crop each off-season. Also they will not choose any cover crops which cannot be associated with a crop and will choose plants which can produce edible products. Therefore, this limits the choice to *O. sativa, Z. mays + A. pintoï*, *D. lablab*, or no cover crop in the rainy season and *P. vulgaris*, *S. tuberosum*, *I. batatas*, vegetable or no crops + *A. pintoï, A. sativa, D. lablab, L. multiflorum* or *V. villosa* in the off-season. The total number of possible cropping systems then became 10,235. There were 1,111 systems with rice every year in total. One of the major problems on this kind of soil is the abundance of weeds due to soil fertility and water availability. The best systems in terms of weed control were systems with *A. pintoï*, but they were also the worst in terms of ease of management. The easiest systems to manage were those with *D. lablab* as a cover crop in the off-season. On these kinds of fields famers farmers usually do not want to grow perennial forages as they do not want to 'lock-up' fertile soil with crops of less value. However, as the soil is fertile and water available all year round, it is possible to grow forage during the off-season. While keeping the same objective of growing rice every year, the best system in terms of forage production was *O. sativa* on a living cover of *A. pintoï*. In fact *A. pintoï* is a good forage but grown together with rice it needs to be controlled to reduce competition, resulting in less biomass production. Another useful system in terms of rice and forage production was the annual sequence between *O. sativa* during rainy season and *V. villosa* in the off-season. Furthermore *V. villosa* can be intercropped with vegetables, combining rice, cash crops and forage production.

5.4. Discussion

5.4.1 Features of PRACT

Simulations made on the four kinds of fields gave contrasting results in terms of the number and the nature of cropping systems selected before and after applying the rules. The characteristics of the agronomic units drive the range of plant species that can be selected and therefore the total number of cropping systems that are feasible. By applying agronomic rules and crop choices we are able to drastically reduce the number of potential cropping systems. Other tools, such as Lexsys, Pasture Picker, Tropical Forages select a forage or cover crop for a specific environment (CTAHR, Cook et al., Robert, 2010; CSIRO, 2012; FAO, 2012c) but have not been designed to consider potential for intercropping or crop rotations. Tools such as ROTAT (Dogliotti et al., 2003) or ROTOR (Bachinger and Zander, 2007) are designed to select crop species in time or space, but deal with fewer plants, and simpler agronomic rules than PRACT. For example, ROTAT generates a maximum of 250,000 cropping systems over seven years. This is far less than the number of combinations over three years that we began with. In fact the possibility of having intercrops and successions of crops and cover crops and of growing during the off-season drastically increases the number of possible cropping systems compared to conventional systems without cover crops.

5.4.2 Steps in designing CA cropping systems

As described in Section 5.2, we identify six kinds of information that can be used to design new cropping systems. These kinds of information can be obtained in different ways which we discuss below.

5.4.2.1 Crop and Cover crop adaptation to local biophysical conditions

Crop and cover crop adaptation to local biophysical conditions can be obtained in different ways. First, from current observations or previous experimental results in the region. Often, cover crops have been tested as forage, green manures or as cover crops for perennial plantations (coffee, oil palm) (Bradshaw and Lanini, 1995; Matos et al., 2008). Thus substantial information can be gathered regarding the adaptation of different species to soil, temperature, rainfall pattern and sometimes pests and diseases (e.g. Tropical Forages, Cook et al., 2012) Secondly, if the exact species have never been cultivated it is also possible to extrapolate their likely behaviour from similar or related species. For example, *A. pintoï* and *A. repens* are quite close in terms of biophysical adaptation. But precautions must be taken, as for some species the different varieties show quite heterogeneous behaviour. Thirdly, and perhaps most importantly, substantial information exists on the adaptation of crop and cover crop species from experience in comparable agroecological conditions in the tropics. For example, tools such as Homologue can be used to identify regions with similar agroecological conditions around the world where species have been tested previously (IITA, 2010). It only requires being able to compare the ecology of both regions. But it is not always easy to define similarities, as in general not all components of the biophysical parameters perfectly match from one situation to another. Various methods have been proposed to combine and weight agroecological parameters (O’Brien, 2004; Jarvis et al., 2008). Fourthly, in theory simulation modelling could also be used to generate such information but in practice few crops and cover crops have been studied or modelled in sufficient detail to predict adaptation to new conditions. Fifthly, it is also possible, and often desirable, to carry out experiments *in situ*.

5.4.2.2 Agroecological functions of cover crops

In this study we used expert knowledge to characterize the plants in terms of agroecological functions (Husson et al., 2009; Seguy et al., 2012). Such information can also be derived from the literature and other databases (Robert, 2010). On the one hand, in CA system the impacts in terms of agroecological functions are often related to the amount of biomass produced by crops and cover crops (Govaerts et al., 2006b; Limon-Ortega et al., 2006; Smets et al., 2008; Virto et al., 2011). On the other hand, crop biomass productivity is strongly linked to its potential competitive ability. Thus, the issue is often to identify not the most productive cover crop but the cover crop which does not compete in time or space with other commercial crops. An additional difficulty can be the specific behaviour of each cultivar in different environments. For example, biomass production and N_2 fixation can vary greatly even within the same species (Giller et al., 1997; Giller, 2001).

5.4.2.3 Intercropping crops and cover crops

The possibility and impact of intercropping crops and cover crops can be derived from databases and the literature. But it is much more complicated because of competition for nutrients, water, light and interactions related to pest and disease incidence. Modelling of the multiple interactions in multispecies systems remains a major challenge (Malézieux et al., 2009). Tixier et al. (2011) used a simple model focusing on radiation interception and based on species traits. Other studies use more detailed crop models to predict partitioning of different resources such as radiation, water and nitrogen between the two crops (Baumann et al., 2002; Shili-Touzi et al., 2010) or between trees and crops (Noordwijk and Lusiana, 1999). A promising way could be to use models developed for crop and weed interactions (Bastiaans et al., 2000). These models take into account weed control management operations and similarities can be extrapolated to cover crop management. Furthermore, the ideal models should take into account the three-party interaction between crops, weeds and cover crops (den Hollander et al., 2007a; b). In our case, compatibility for intercropping had been formalized in a technical manual that considered different combinations of cover crops and crops based on extensive field experiments (Husson et al., 2009).

5.4.2.4 Agroecological functions of the cropping system

The agroecological functions of a cropping system should be assessed at least over one rotation and not only one season or year. Criteria to evaluate the cropping systems can be directly extrapolated from plant characteristics, as in PRACT (e.g. crop production). But some of the functions at cropping system level are determined by the combination (intercrops or sequences) of different plants. The evaluation of cropping systems in terms of yields and agroecological functions can be extrapolated from single crop characteristics when they are combined in simple sequences as a monocrop, but it is much more complex in the case of crop and cover crop intercropping.

The agroecological evaluation of cropping systems, both *ex-ante* or *ex-post*, is possible with tools such as PRACT or other approaches (Sadok et al., 2009; Tixier et al., 2011). But it makes no sense to evaluate the cropping system *per se* without taking into account the social or economic perspectives. For example, the introduction of a cover crop is likely to increase labour requirements, at least in the short-term, as well as the complexity of management for the farmer. Such modifications may suit only some farmers. When wishing to evaluate cropping systems by modelling or using a multicriteria approach, this needs to be done at farm level, as done in the Alaotra region, for example, by using linear programming (Chapter 4) or with other tools in different systems (Sadok et al., 2009; van Wijk et al., 2009; Le Gal et al., 2010, 2011)

5.4.2.5 Possible uses and further development of PRACT

If we refer to the typology proposed by van Ittersum et al., (2003), up to now the field of application for PRACT has been more related to research or education than to the decision-making process. We discuss below the possible evolution of PRACT in general and what is required to move toward a decision support system (DSS).

PRACT is sufficiently flexible to allow new crops and cover crops to be added, characteristics of the different species to be changed and adjusted, or selection rules to be added, revised or removed. The iteration between analysis of the potential combinations in output and adding new characteristics and rules can be done quite quickly in an interactive way. Thus, PRACT can be used to select cropping systems to be tested in the field. One of the main issues is to reduce the number of cropping systems to facilitate their comparison by famers and technicians. Selection of cropping systems to be tested could also be done together with farmers in a participatory approach before starting to test cropping systems in the field. This is a rapid approach to understanding farmers' goals and constraints and matching cropping systems to them. It can also be argued that if a large selection of systems can be compared, it is important to test crops and cover crops which do not fit in with farmers' wishes *a priori*. For example, in Section 5.3.1 we saw that systems with *S. bicolor* are the best for improving soil quality. In a first round of simulation it could be interesting to include *S. bicolor* in the initial set of crops chosen, so as to allow systems to be selected that include an example of cropping systems focused on soil improvement rather than on crop production alone. An array of systems could then be used as examples to discuss with farmers and extension workers the possibilities of including such a cropping system in their farm plans. If the number of crops and cover crops is reduced too quickly, the potential for discovering novel, innovative combinations is reduced, as are the options that can be discussed with farmers. When comparing cropping systems selected by PRACT with those of farmers, three situations can occur: they can be equal, *a priori* worse or *a priori* better from an expert's point of view. In the second case technicians' and farmers' knowledge can be translated into new rules or parameters in PRACT to prevent PRACT from generating irrelevant cropping systems from their point of view. At least the interaction for redefining these rules can be very informative for both farmers and extension agents. In the last case, the new proposed systems can be selected for testing on a small area to evaluate them under real conditions.

PRACT is also useful for generating a large range of cropping systems as inputs for farm modelling and for scenario testing. For example, as shown by Dogliotti et al., (2005), linear programming can be used to select from among the cropping systems which better suit farmers' goals and constraints.

If PRACT were used as a DSS, we recommend that it should be used as a stand-alone tool in the first instance, as users generally do not like "black boxes" where equations or calculations are not clear (McCown, 2002). Secondly, PRACT should be regarded as a "learning" tool rather than a tool that provides definitive advice. Thirdly, the tool and any DSS version of PRACT are designed for use by extension workers and scientists - not for direct use by farmers in Madagascar who have neither the means nor interest to use such a tool.

Lastly, we encountered limitations in the maximum number of simulations that could be handled by Microsoft Access 2007®. Thus, further improvement of PRACT would require the application to be developed within a more powerful database manager.

5.5. Conclusions

Generating a list of commercial crops and cover crops, intercropped or in sequence, to be combined in a cropping system is more complex for CA systems than for conventional cropping systems. The numbers of possible combinations increase factorially by adding cover crops as intercrops or in the off-season in sequence. The agronomic rules are also more complex, as the need to produce biomass for soil cover or forage, without reducing crop production, restricts the feasibility of crop and cover crop intercropping or sequences. The potential number of combinations, together with the number of agronomic rules to be taken into consideration, make CA cropping systems more difficult to design for local conditions, even without considering the technical management of each crop and each cover crop. This complexity is, perhaps, one of the reasons for the small number of CA cropping systems developed by farmers themselves in sub-Saharan Africa. Even after applying agronomic rules, the number of feasible (from a biophysical point of view) cropping systems can still be large. Further filtering of cropping systems is therefore carried out considering farmers' main preferences, goals and constraints, meaning that the evaluation of the cropping system *per se*, with no reference to a type of farm, is not relevant. Furthermore, even for a specific type of farm, the adequacy of a cropping system should be considered in relation to other activities (crop, animal production and off-farm activities). Finally, the agroecological functions of a crop are not always known, easy to measure and even less easy to simulate. This is even more problematic when dealing with intercrops or rotations where interactions between plants can have strong impacts on the expression of these functions. Up to now, few models have dealt with this problem and they often consider interactions concerning only a single function, such as N (Baldé et al., 2011), or two functions, such as competition with weeds and N (Tixier et al., 2011). It is therefore impossible to rely on modelling alone for an *ex ante* evaluation of cropping systems. But modelling could be useful for explaining and debating about expert knowledge. Modelling could also be used together with on-farm experiments and farmer evaluations of cropping systems to select promising systems and management options, even though it has not often been used for CA cropping systems (Giller et al., 2011; Tittonell et al., 2012).

Chapter 6

General discussion and conclusion

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6.1 Introduction

As cropping systems provide many products and services, their *ex-ante* or *ex-post* evaluation cannot be made useful on the basis of a single criterion. In particular, for CA cropping systems the evaluations should be made regarding their expected impacts or agroecological functions. These functions, apart from grain production, can be grouped into eight categories (Fig. 1.1). The achievement of these functions depends on how each of the three CA principles is implemented. In Chapter 5 we explored the linkages between the degree of implementation of CA principles and the achievement of agroecological functions.

We have seen in Chapter 2 (Objective 1) that the application of the first CA principle (direct seeding) alone did not have a significant impact on cotton production in the Far North province of Cameroon as yields obtained under no till with or without mulch were not different from those with tillage. The second principle (soil cover) had an impact, as yields were greater under no till with mulch than under no till without mulch. The last principle (crop diversity) was implemented by intercropping a cover crop with cereals that led to doubling the quantity of the above-ground biomass produced. The effect of no till and mulch on the duration of the flowering period and final yield was an indicator of a positive effect of CA on the “water balance” function. Regarding technical management, no tillage with mulch was found to use more herbicide spray and fertilizer.

In Chapter 3 (Objective 2) we have shown that the second principle (soil cover) was strongly linked with the third principle (crop diversity). In farmers’ rice fields in the Alaotra region of Madagascar the soil cover of CA fields can vary strongly. It ranged from 30 to 84% even when considering the same kind of field, depending on the cover crop used and the amount of biomass produced. The range of variation was much greater when different kinds of fields were considered. Of course, whether the different agroecological functions of CA can be fulfilled depends on the amount of biomass production, residue management and resulting soil cover. Chapter 3 investigated the relationships between the quantity of biomass produced and retained, and the soil cover this provided for a range of different crops and cover crops. We used these relationships to explore the variability of soil cover that could be generated in farmers' fields, and to estimate how much of the biomass could be removed for use as livestock feed, while retaining sufficient soil cover. The study showed that under farmers' conditions in Madagascar, the production and conservation of biomass was not always sufficient to fulfil all the above-cited agroecological functions of mulch. Furthermore, the thresholds varied for the different functions desired. For example, partial removal of biomass to be used as forage may have no effect in reducing the effectiveness of the mulch in erosion control but the same degree of removal may reduce notably the potential to control weeds.

As the balance of potential benefits derived from removal of biomass for feed varied according to farm constraints and goals, in Chapter 4 (Objective 3) we modelled the potential benefits of above-ground biomass export to feed cattle at farm level. We studied Malagasy farms of different sizes to explore the relationships between raising dairy cows and CA. Our aim was to explore trade-offs and synergies between combinations of CA practices (more or less biomass export), and the size of dairy cow herds (with animal production depending on biomass for forage). We applied a constraint on the minimum soil cover to be kept at the end of each year for CA fields: from 30 to 95%. We simulated two scenarios of milk market: a small milk market with low forage price, and an open milk market with higher forage price. Three kinds of farms were simulated. Changing the degree of soil cover to be retained on CA plots did not significantly modify the total farm net income. It was more strongly influenced by the characteristics of the milk market. Overall, CA systems can be beneficial to dairy cow farmers because of the forage produced, although the milk market and thus the value of biomass for forage, has a strong influence on the way CA can be implemented at field level. Even with a limited number of possible cropping activities (28) the number of possible combinations of cropping systems is numerous. In fact the total number of potential cropping activities even for one kind of field is very high when considering all possible crops and cover crops that may be grown.

This led us to explore the whole range of possible cropping systems in given field situations in Chapter 5 (Objective 4). In this chapter the focus was on the third principle of CA (crop diversity). Our aim was to propose a method for designing CA cropping systems adapted to each of these situations. We formalized the underlying hypothesis behind the design, based on field characterisation, cover crop adaptation to different field types, the possible intercrop combinations, and sequences of crops and cover crops. This work showed that even after applying agronomic rules from a biophysical perspective the number of feasible cropping systems remained large. The number of cropping systems was then reduced considering farmers’ preferences, goals and constraints at farm level. The evaluation of the cropping systems designed *per se* without reference to farm types was not relevant to the real farming situation. In the same line and even for a given type of farm, the adequacy of a cropping system should be considered in relation with other activities (crop, animal production and off-farm activities).

Some CA functions (Fig. 1.1) have not been explored in detail in the previous chapters of this thesis, for example pest and disease control, C sequestration, runoff and erosion, and weed control, mainly because our studies on these functions in Madagascar are still ongoing. These functions may also have significant impacts on crop production both in the short or long term. In the following parts we discussed the links between the achievement of these four functions and above-ground biomass exportation. The underlying idea was that the biomass produced could be used to feed animals. This export was beneficial for animal production but could be detrimental to crop production sustainability. We explored the theoretical relations between crop residue management and efficiency of the cropping system regarding the four agroecological functions detailed hereafter.

6.2 Runoff and erosion

In most of the countries where CA has been introduced, the principal goal has been to reduce soil erosion through reducing runoff (Lal, 1976; Bolliger et al., 2006; Hobbs, 2007; FAO, 2012a). The relationship between soil cover and runoff and erosion is well documented. For example in the RUSLE 2 model the effect of an increasing soil cover on erosion reduction is described by the equation: $MF=100e^{-aC}$, where *MF* is erosion in percent of a control plot with no cover, "*a*" a constant and *C* the soil cover in percent, (Fig. 6.1). At the minimum threshold of 30% of soil cover used in Chapters 3 and 4, the mulch cover reduced interrill erosion up to 47% and rill erosion to 19%. In further modelling, for example in an expansion of the GANESH model, it would be possible to integrate the relationship in Fig. 6.2 to define thresholds and trade-offs directly in terms of soil erosion.

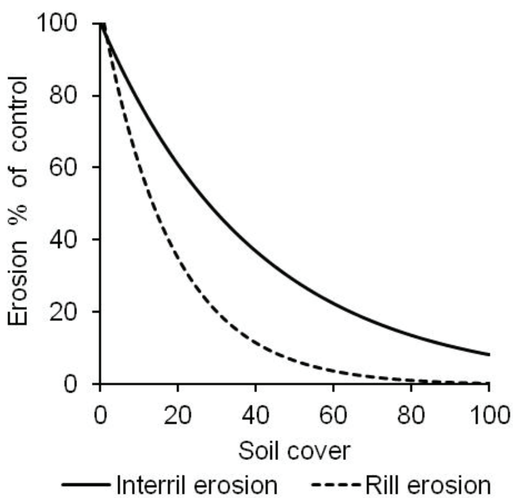

Figure 6.1. Relationships between soil cover and percentage of rill and interrill erosion compared with a control with no mulch (Renard et al., 1997).

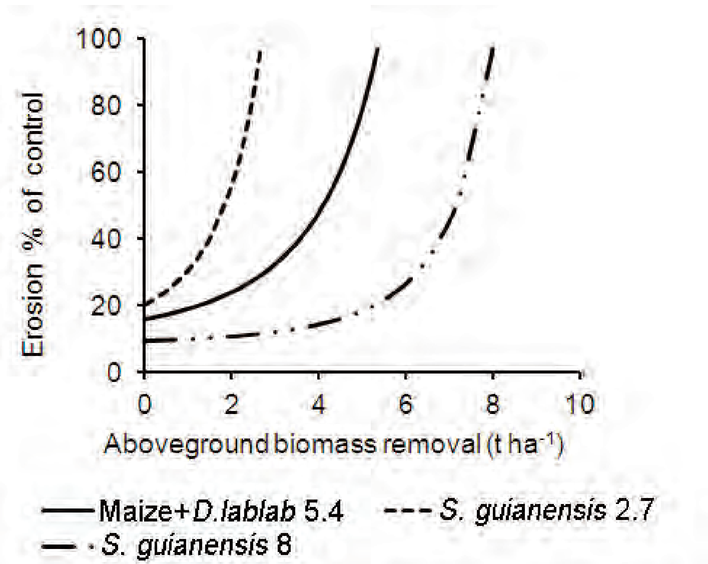

Figure 6.2. Interrill erosion (in percent of a bare soil control) for three different types of mulch: Maize+dolichos at a rate of 5.4 t ha^{-1}, *Stylosanthes* at 2.7 t ha^{-1}, *Stylosanthes* at 8 t ha^{-1}. Mulch quantity and soil cover data from Naudin et al. (2011) and the relationship between soil cover and erosion control from Renard et al. (1997).

Of course the mulch quantity changes in the course of the year as mulch decomposes. Thus, as for C input, the effect of soil cover on soil erosion should be assessed over time. Usually it is important that soil cover be most complete at the beginning of the rainy season when rainfall is intense. For example, in Madagascar the patterns of soil cover differed widely between CA and conventional cropping systems, but also between the different kinds of CA cropping systems. Thus the potential effect on erosion control varied in the same way (Fig. 6.3).

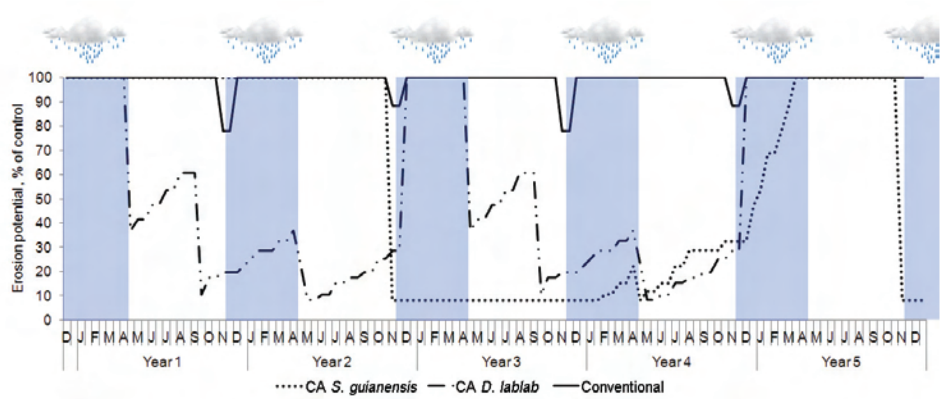

Figure 6.3. Effect of mulch on interrill erosion potential percentage of control for three cropping systems over five years in Madagascar. Calculated with soil cover data from Van Hulst et al. (2011).

6.3 C sequestration

Many studies have shown contrasting effects of CA on soil organic carbon (SOC) stocks (Govaerts et al., 2009b). CA impacts C sequestration in two ways: reduction of SOM decomposition by reducing tillage effects on aggregate stability, and increase in C input by introducing cover crops. We have not investigated the effect of CA on SOC decomposition in our local conditions. But as shown by Virto et al. (2011) and Corbeels et al. (2006), C input is the main factor explaining differences in SOC storage. Thus a comparison of cropping systems could be made based on the total biomass produced as potential for increasing SOC stocks. Then the relationship between biomass export and C input to soil is perhaps the easiest to determine. See Fig. 6.4 for an example based on data from Madagascar.

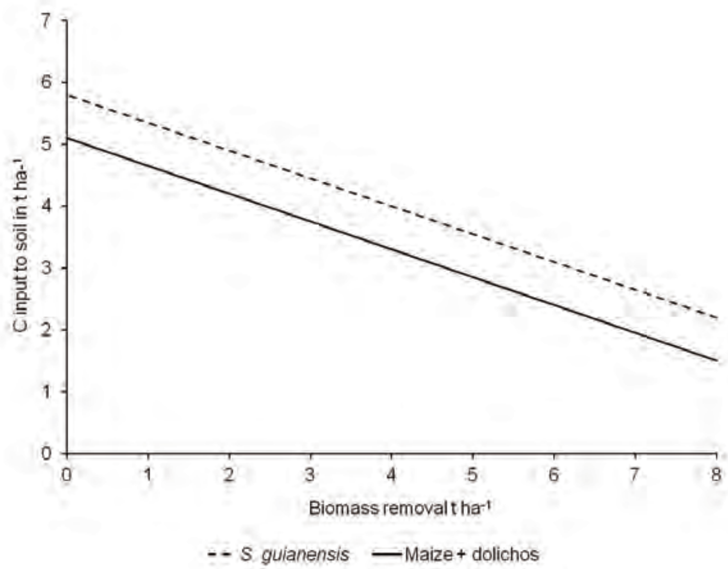

Figure 6.4. C input as a function of biomass removal for two cover crops grown preceding rice: *S. guianensis* and Maize + *Dolichos lablab*, calculated with data from Naudin et al. (2011a). Assuming that C input to soil from below-ground parts (roots and exudates) are 2.2 t ha^{-1} for *S. guianensis* and 1.5 t ha^{-1} for maize+dolichos extrapolated from Kuzyakov and Domanski (2000).

6.4 Pest and disease control

Pests and diseases of the main crops are affected in CA by, among others: i) the cover crop in rotation, ii) the physical effect of mulch on local conditions, iii) the nature of residues and their chemical composition, iv) changes in canopy structure due to changes in crop management and/or development calendar.

The nature of cover crop in rotation can have effects through various mechanisms: temporary disruption of pest/pathogen cycles through non-host effects; resource concentration/dilution and spatial disruption of pest dynamics / pathogen epidemics; pest deterrence or repellence; pest stimulation or attraction; below-ground allelopathic effects; stimulation of soil pest-pathogen antagonists; crop physiological resistance through improved nutrition; effects through provision of alternative food to natural enemies of crop pests; effects due to provision of refuges/shelters for predators due to vegetative structural/architectural characteristics; effects through microclimate alteration or as physical barriers (Ratnadass et al., 2011). From the literature review and on site or mesocosm experiments we have seen that few cover crops used in Madagascar have shown effects on insects or diseases in CA systems. However, effects on nematodes are more widely documented in the literature but rarely used as criteria to design new cropping systems (Quaranta, 2010; Naudin et al., 2011b) (Tab. 6.1).

Table 6. 1. Inventory of actions of 21 cover crops used in Madagascar on crop pests, references from the literature**.** Effective parts of plants: R: roots; S: shoots/stems; L: leaves; MD: missing data, *i.e.* unknown. Mechanisms (Ratnadass et al., 2011): (A) temporal pest/pathogen cycle disruption via non-host effects; (B) resource concentration/dilution and spatial disruption of pest dynamics / pathogen epidemics; (C) pest deterrence or repellence; (D) pest stimulation or attraction; (E) below-ground allelopathic effects; (F) stimulation of soil pest/pathogen antagonists; (G) crop physiological resistance via improved nutrition; (H) effects via provision of alternative food to natural enemies of crop pests; (I) effects via provision of refuges/shelters for predators due to vegetative structural/architectural characteristics; (J) effects via microclimate alteration; (K) physical barrier effects.

Cover crop Family - Species	**Pest targeted Type**	**Name**	**Effective part of the plant**	**Mechanisms**	**References**
Arachis pintoï, A. repens	Nematoda	*Pratylenchus loosi, Meloidogyne incognita, Meloidogyne paranaensis, Roylenchus reniformis*	MD	Unknown	Luc et al., 2005
	Insecta	*Diaprepes abbreviatus*	S, L	K	Lapointe, 2003
	Insecta	*Cyrtomenus bergi*	S, L	A	Riis et al., 2005
Cajanus cajan	Nematoda	*M. incognita, Meloidogyne javanica, R. reniformis, Heterodera cajani, Pratylenchus zeae, Pratylenchus sudanensis*	R	A	Sharma et al., 1993, 2000; Catherine et al., 2002; Luc et al., 2005; Spurthi et al., 2009
	Insecta	*Spodoptera exigua*	MD	Unknown	Spurthi et al., 2009
Crotalaria grahamiana, C. spectabilis, C. juncea	Nematoda	*M. incognita, Meloidogyne arenaria, Meloidogyne javanica, R. reniformis, Pratylenchus brachyurus, P. zeae, Pratylenchus. coffeae, Radopholus similis*	R, L	A, E, F, G	McSorley, 1999; Catherine et al., 2002; Wang et al., 2003; Luc et al., 2005
Desmodium uncinatum	Nematoda	*Hoplolaiminae genera, Meloidogyne spp.*	MD	Unknown	Luc et al., 2005
	Insecta	*Busseola fusca, Chilo partellus*	S, L	C, G,	Khan et al., 2000, 2001; Khan, 2008
Mucuna pruriens	Nematoda	*Belonolaimus longicaudatus, Paratrichodorus minor, Criconemella ssp., Scutellonema ssp., Heterodera glycines, Tylenchorhynchus claytoni, M. incognita, M. javanica, P. brachyurus, Ditylenchus sp, Aphelenchoides sp, Aphelenchus avena, Tylenchus sp , R. reniformis*	R, L	E, F, J	Queneherve et al., 1998; Blanchart et al., 2006

V. unguiculata	Nematoda	*M. incognita, M. javanica, M. arenaria*	R	A, E	McSorley, 1999; Catherine et al., 2002
	Insecta	*C. partellus, Chilo orichalcociliellus, Sesamia calamistis*	S, L	A, G, K	Skovegard and Pats, 1997
Vicia villosa	Insecta	*Delia radicum, Plutella xylostella*	S, L	Unknown	Mangan et al., 1995; Dixon and Dickson, 2007
	Nematoda	*M. arenaria, Meloidogyne artiellia*	R	A	Moneim and Bellar, 1993; Mosjidis et al., 1993
Stylosanthes guianensis	Nematoda	*M. incognita, M. javanica, P. brachyurus*	R	A	Catherine et al., 2002; Luc et al., 2005
Trifolium semipilosum, T. repens	Nematoda	*Meloidogyne trifoliophila*	R	A	Mercer et al., 2004; Barrett et al., 2005
	Insecta	*Heteronychus arator*	R	C	King, 1981
Graminae					
Avena sativa	Nematoda	*Meloidogyne spp.*	R, S, L	B	Catherine et al., 2002
	Insecta	*Tetanops myopaeformis*	S, L	H, K	Dregseth et al., 2003
	Acarina	*Oligonychus punicae, Scirtothrips citri*	S, L	D	Bugg, 1991
Brachiaria ruziziensis, B. brizantha, B. humidicola.	Nematoda	*M. incognita, M. javanica*	MD	Unknown	Catherine et al., 2002; Dias-arieira et al., 2003
Cynodon dactylon	Nematoda	*M. incognita*	MD	A	Johnson et al., 1995
	Insecta	*Spodoptera frugiperda*	MD	Unknown	Jamjanya and Quisenberry, 1988
Eleusine coracana	Nematoda	*R. reniformis*	R	A	Asmus et al., 2008
Lolium multiflorum	Nematoda	*R. reniformis*	MD	Unknown	Jones et al., 2006
	Insecta	*L. phyllopus*	MD	Unknown	Bugg, 1991
Brassicaceae					
Raphanus sativus	Nematoda	*Heterodera schachtii, M. incognita, Meloidogyne halpa, R. reniformis, Trichodorus* sp., *Pratylenchus* sp.	R	A, E	Rodriguez-Kabana et al., 1992; Cuadra et al., 2000; Crow et al., 2001; Catherine et al., 2002; Kokalis-burelle, 2006

In general, soils under mulch may host more invertebrates (in both number and type) than bare soils (Blanchart et al., 2007; Brevault et al., 2007; Maria de Aquino et al., 2008; Rabary et al., 2011). CA proponents argue that this biodiversity can promote natural control of pests and diseases (Hobbs, 2007; Kassam et al., 2009). But even within the same study (Table 6.2) these effects are not systematic, and CA systems can have positive, negative or no effects on pest control.

Table 6.2. Some examples of studies showing contrasting effects of CA on pest control in Madagascar and Cameroon.

					Comparison of CA with control			
	Comparison	Country	Crop	Pest	More pest	No difference	Less pest	Reference
Direct planting	No till *vs* ploughing	Cameroon	Cotton	Herbivore insects in general		X	X	Brévault et al. 2007
Permanent soil cover	No till with or without mulch	Cameroon	Cotton	Millipedes	X			Brévault et al. (2008)
				Aphids		X		Brévault et al. (2008)
				Herbivore insects in general	X	X	X	Brévault et al. (2007)
Crop diversity	No till with grass, legume or no cover crop	Cameroon	Cotton	Herbivore insects in general		X		Brévault et al. (2007)
	Rice, soybean or no residue	Madagascar	No	Plant-feeder nematodes		X		Villenave et al. (2010)
	No till with 7 cover crops *vs* conventional tillage	Madagascar	Rice	White grubs	X	X	X	Rabary et al. (2011)
Combination of factors	No till *vs* conventional	Madagascar	Rice	White grubs	X			Ratnadass et al. (2006)

Furthermore, to the best of our knowledge, no studies directly link various degrees of soil cover or quantity of mulch with the effect on crop pests, meaning that it is difficult to link biomass removal and pest control. If we draw a theoretical relationship between above-ground biomass removal and pest pressure, different kinds of curves are possible.

- No effect of biomass removal, the pest pressure is the same with bare soil as with a cover crop and mulch has no effect on pests (Fig. 6.5, line A)
- No effect of biomass removal, the pest pressure is the same with bare soil as with a cover crop which had an effect while being grown *in situ* the year before, but the residue had no effect (Fig. 6.5, line B)
- Increase of pest pressure due to biomass removal, linear (Fig. 6.5, line C) or not (Fig. 6.5, line D and E)
- Decrease of pest pressure with biomass removal, linear (Fig. 6.5, line F) or not (Fig. 6.5, line G and E)

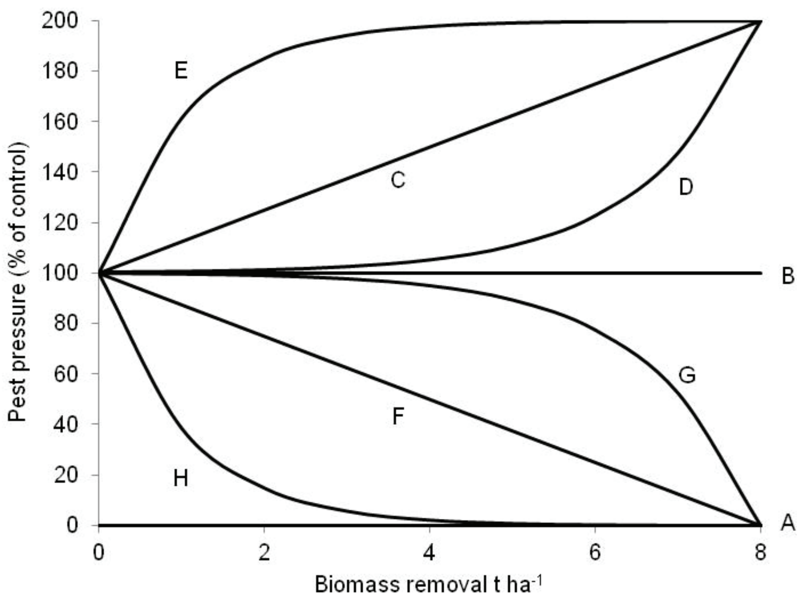

Figure 6.5. Theoretic relation between biomass removal (with an initial biomass of 8 t ha^{-1}), and pest and disease pressure on the crop compared with a control situation (bare soil). A/B no changes compared with the bare soil control, C/D/E increase in pest and disease pressure with decreasing soil cover, F/G/H decrease in pest and disease pressure with decreasing soil cover.

In conclusion the nature of the cover crop in rotation, the presence of mulch, and the suppression of tillage are maybe more important than the amount of mulch or the percentage of soil cover. Because of the variety of pests and diseases and the complexity of biological mechanisms, the relationships between residue management and pest and disease control are more complex relationships to understand compared with other functions.

6.5 Weed control

CA has an impact on weed pressure through various mechanisms (Table 6.3).

Table 6.3: Effects of CA on weed pressure adapted from Chauhan and Johnson (2009)

Favourable for crop	Unfavourable for crop	Can be both
Seed predation	Interception of herbicides by thick surface residues	Vertical weed seed distribution
Early crop sowing possible		Lack of disruption of perennial weed root
Crop rotation complexity, disruption of weed cycle		Moisture conservation
Mulch allelopathic effects		Change in weed
Decreasing light transmittance		
Competition between weeds and cover crop		

Our experimentation on this topic in the Lake Alaotra region of Madagascar showed that the total control of weeds in rice crops only appears with very large quantities of mulch: 20 t ha^{-1} of mulch (Fig. 6.6), or equivalent to twice the quantity of mulch to cover 99% of soil (Fig. 6.7). We also found that the weed cover or weed emergence was often higher on soil covered up to 99% by mulch than on soil with no cover.

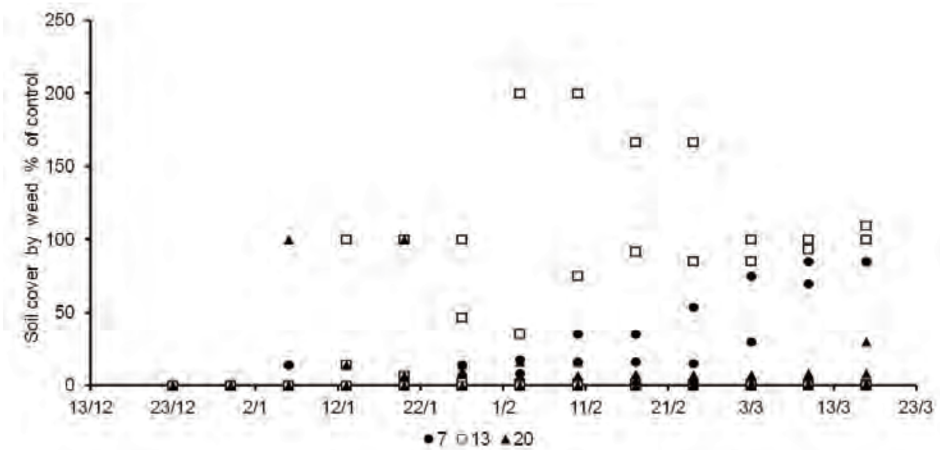

Figure 6.6. Development of soil cover by weeds between rice rows during the 2009-2010 cropping season; three rates of *Dolichos lablab* mulch (7, 13, 20 t ha^{-1}) values expressed in percent of control (no cover), unpublished results.

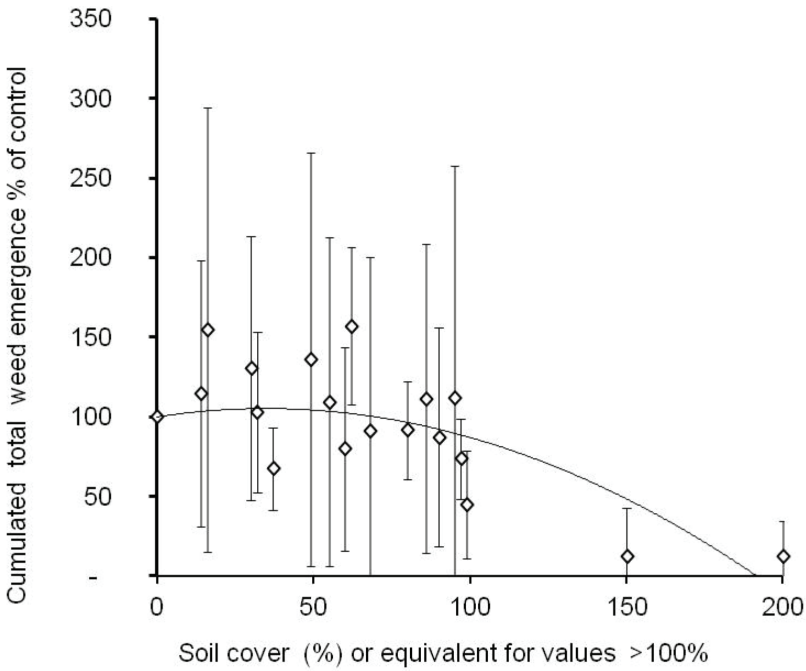

Figure 6.7. Cumulative emergence of weeds during the 2010-2011 or 2011-2012 cropping seasons. Emergence expressed in percent of control plot (no cover), mean and standard deviation. Model: $y = -0.0043x^2 + 0.2987x + 100$, $R^2 = 0.5146$, unpublished results.

The potential yield reduction because of competition with weeds, referred to here as weed pressure, is not linearly related to soil cover. Because i) mulch can have allelopathic effects not related with the percentage of cover or mulch quantity, ii) even the emergence of one species is seldom linearly related with soil cover (Fig. 6.7, Teasdale and Mohler, 2000), this is likely to be even less the case when considering a mixture of various weed species and all other stages of weed development. Thus we propose two shapes of theoretical relationships between soil cover and weed pressure in Fig. 6.8.

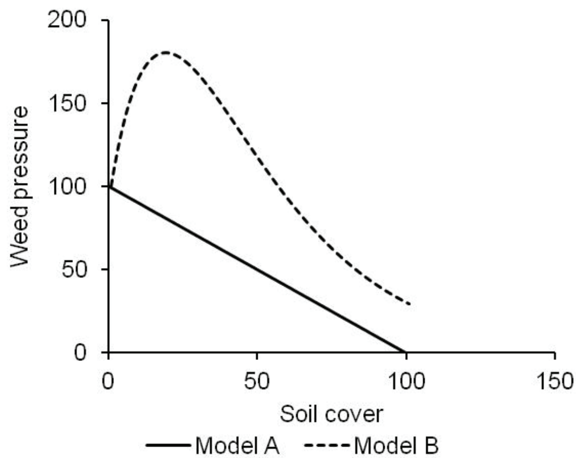

Figure 6.8. Theoretical relationships between soil cover and weed pressure.

Using Model B of Fig. 6.8 and biomass data from Chapter 3 (Naudin et al., 2011a) we can draw a theoretical relation between biomass removal and weed pressure using biomass data from Madagascar (Fig. 6.9).

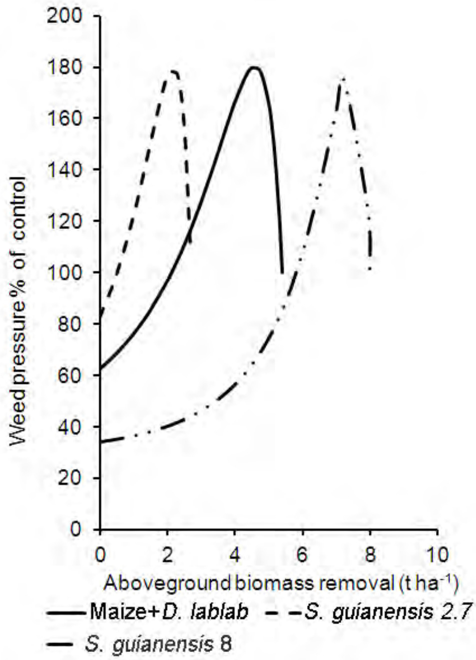

Figure 6.9. Theoretical relationships between biomass removal and weed pressure, based on relationships between soil cover and emergence (Naudin 2012, Teasdale and Mohler, 2000) and the assumption that weed control is more difficult for farmers when there is only partial cover. Biomass data from Naudin et al. (2011) mulch of maize + *D. lablab*, *S. guianensis* at 2.7 t ha^{-1}, *S. guianensis* at 8 t ha^{-1}.

Of course weed pressure in the crop and farm management varies greatly between cropping systems (*e.g.* flooded or not), farm types (*e.g.* with great labour availability or without), access to herbicides or not. For example in North Cameroon (Chapter 2) even smallholder farmers, because they have access to loans, herbicides, pesticides and fertilizers through the cotton company, place less importance in weed control than farmers of the Lake Alaotra region. In that part of Madagascar, herbicide use is uncommon because farmers rely on their own cash to buy pesticides, and these inputs are expensive, compared with farm income, and few outlets for agrochemicals exist. Even in the same region, the degree of weed control differs highly between farm types.

6.6 Balancing CA functions

If we assume that the main factor determining CA success in developing countries is competition for plant biomass mulch or for cattle feed, then the benefits of keeping mulch on soil surface must be balanced against the use of biomass as forage. This issue is assessed at farm level.

I propose some theoretical relationships to determine trade-offs between biomass export from field to feed animals and the agroecological functions of CA in Fig. 6.10. Up to now these relationships have only been partially established in developing countries. More effort should be made to understand them. Quantitative assessments are needed to evaluate cropping systems, *ex-ante* or *ex-post*, with multi-criteria methods to enable design of new appropriate options. Such assessments are also needed to provide quantitative tools to development agents and to farmers with regard to trade-offs around biomass uses.

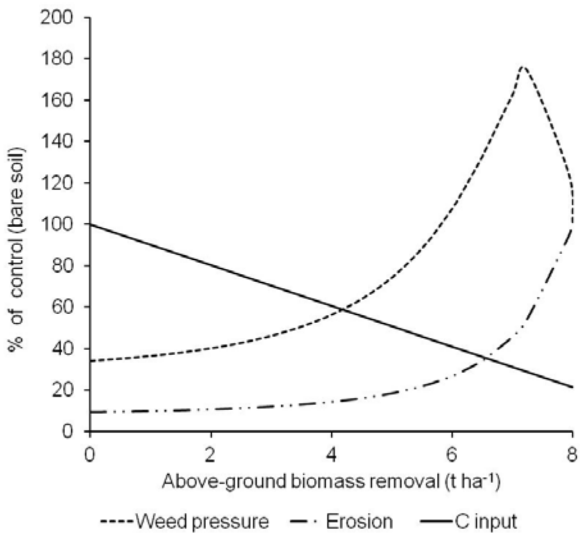

Figure 6.10. Theoretical relationships between biomass removal and weed pressure, erosion control and C input. Simulation for *S. guianensis* with 8 t ha^{-1} of above-ground biomass. Based on biomass data from Chapter 3, relations between soil cover and emergence (Teasdale and Mohler, 2000; Naudin et al., 2012) and the assumption that weed control is more difficult for the farmer. Biomass data from Naudin et al. (2011).

6.7 General conclusion

The main hypothesis of my thesis is: "*The benefits of Conservation Agriculture among diverse smallholder farmers are explained by the trade-offs between field and farm level".* This hypothesis has been addressed in various ways in the preceding chapters. In Cameroon the contract with the cotton company is globally favourable for the adoption of CA. Thus the risk at farm level to implement CA is quite low compared to the potential agronomic benefit at field level in the Far North province. In Madagascar farm characteristics and milk market drive the possibility or not to keep crops and cover crops biomass as mulch or to use it to feed cattle. The selection and evaluation of new CA cropping system is also almost impossible to do without taking into account farm constraints and objectives. But as I argue below the first step to understand these trade-offs is to quantify biomass production and uses and the explicit benefits from biomass uses at field and farm level.

The debate around priorities in terms of agronomic research for developing countries has become increasingly dominated by political ideology and less by scientific argument (Sumberg et al., 2012). Regarding CA, the proponents and critics can always find scientific works to support their arguments (Hobbs, 2007; Giller et al., 2009). The studies regarding positive or negative effects of CA are not consistent; depending on the researchers, CA impacts have been found positive, negative, or null compared with conventional techniques on agroecological functions of cropping systems and their productivity (Giller et al., 2009; Verhulst et al., 2010; Baudron et al., 2011). There is sufficient evidence that most of the effects of mulch are related to biomass quantity and soil cover (Scopel et al., 1999; Teasdale and Mohler, 2000; Corbeels et al., 2006; Govaerts et al., 2008; Smets et al., 2008). But as we have seen in the introduction, very few studies give details on the quantity of mulch produced and even fewer evaluate soil cover in CA treatments when comparing them to conventional ones. As for other ecological intensification approaches (Doré et al., 2011) I argue that it could be informative to implement meta-analyses linking CA impacts and quantities of biomass produced in cropping systems.

Furthermore, I formulate the hypothesis that well-managed cropping systems maximize biomass production and the associated agroecological functions without competing in time or space with crop production and other farm activities. As seen in Chapter 4, I infer that biomass production for CA and livestock can find a mutually beneficial equilibrium.
At the same time there is still confusion among authors about what CA actually is. Some papers are supposed to relate to CA but in fact their CA treatment is a “no tillage” treatment, *i.e.* without mulch and/or without crop diversification (Lahmar et al., 2011). These techniques and studies may be valuable but using the term CA for very different cropping systems creates a smokescreen which confuses the scientific debate. In fact CA proponents and critics include or do not include these kinds of work to emphasize their points. Proponents include the area under “no till” (not complete CA) when they want to show the large spread of CA in the world (Derpsch, 1997, 2007). Thus I recommend a more rigorous description of cropping systems, technical management, residue management, biomass production and mulch cover quantification when reporting experiences on CA. The debate around the usefulness of CA for smallholders in developing countries, in particular in sub-Saharan Africa, is far from closed. I suggest that future debates should be based on more rigorous definitions and quantitative data, as proposed by Giller et al. (2011).

In the end, regardless of what we like to do from a scientific 'design' perspective, it has to meet farmers' needs and goals to succeed in the real world of farming. Purely technical research will not achieve this if farmers do not play a central role in evaluating and feeding back their ideas and evaluations to the world of science and research.

It is not easy to anticipate the future development of CA in Africa, partly because the development of Africa itself is at an historic turning point. Certainly CA will find its place in the drive for an ecological intensification of agriculture in Africa (Schutter, 2010; Snapp et al., 2010). Researchers should participate in the effort by providing strong arguments based on data from real farms and fields, by clearly defining the objects studied, by conducting multi-criteria evaluations of cropping systems, and by understanding the cropping system as an inherent part of the farming system. This thesis work was oriented to contribute to a more peaceful and fruitful scientific debate.

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Appendix

Appendix 1: Labour requirements (man/day/ha) for each crop production activity per two weeks periods,

Appendix 2: Input requirements for each crop production activity.

Appendix 3: Crop production activity outputs (kg/ha) for each period of two-weeks.

Appendix 4: Forage and crop residues nutritive values according to the French feed evaluation system INRA

Appendix 5: Animal nutritive requirements, maximum feed intake, production and and labour needs for the four types of animals

Appendix 6: model formulation of GANESH

Appendix 1: Labour requirements (man/day/ha) for each crop production activity per two weeks periods, one day=eight hours (*e.g.* Oct 1, Oct.2), based on farmers' survey.

Type of field	Soil managen	Crops (+cover crops)	Oct2	Nov1	Nov2	Dec1	Dec2	Jan1	Jan2	Feb1	fev2	mar1	Mar2	Abr1	Abr2	May1	May2	juin1	juin2	jui1	jui2	aou1	Aug2
Irrigated paddy fields	Conventional	Irrigated rice	2,2		2,2	0,7	2,7		1,7					1,8									
Poor water control paddy field	Conventional	Rice/Fallow				1,76	2,64	2,72		3,44						1,2							
		Rice/Vetch				1,44	2,48		2,56				3,12				1,6						
	CA	Rice/Fallow			2,4		2,72		3,52				2,64										
		Rice/Vetch			2,4		2,72		3,52				2,64				1,6						
Alluvial soil	Conventional	Rice/Fallow					3,84		3,52					2,64									
		Rice/Dolichos					3,84		3,52					2,64			1,6						
		Rice/Vetch					3,84		3,52					2,64			1,6						
		Maize/Fallow		1,6	2,56		1,6								2,24								
		Maize/Dolichos		1,6	2,56		1,6								2,24		1,6						
		Maize+Dolichos/Fallow				1,2	2,4	2,56							2,08								
	CA	Rice/Fallow					3,04		3,28					2,96									
		Rice/Dolichos					3,04		3,28					2,96			1,6						
		Rice/Vetch					3,04		3,28					2,96			1,6						
		Maize+Dolichos/Fallow					2,32	3,12									2,16						
Hillsides	Conventional	Brachiaria			1,2																		
		Cassava				1,4	0,8		2														3
		Groundnut				0,6	2,4			2,4						4,8							
		Groundnut+Stylo					1,36	2,64	2,88							2,72							
		Maize		1,6	2,56		1,6								2,24								
		Maize+Dolichos					4,16		3,28								2,32						
		Rice					3,92		2,64					2,96									
		Cassava+Brachiaria			1,2	1,4	0,8		2														3
	CA	Brachiaria			1,2																		
		Rice				2,8			2,64					2,64									
		Groundnut+Stylo						2,48	2,16							2,64							
		Maize+Dolichos					2,56	2,56									2,48						
		Stylo																					

Appendix 2: Input requirements for each crop production activity in terms of seed, fertilizer, manure and pesticides needs expressed in cash terms (kAr/ha/year).

Type of field	Soil management	Crops (+cover crops)	Seeds	Fertilizer +Organic manure	Pesticides
Irrigated paddy fields	Conventional	Irrigated rice	30	0	24
Poor water control paddy fields	Conventional	Rice/Fallow	80	103	26
		Rice/Vetch	150	443	32
	CA	Rice/Fallow	62	84	22
		Rice/Vetch	142	168	29
Alluvial soils	Conventional	Rice/Fallow	77	123	27
		Rice/Dolichos	95	123	27
		Rice/Vetch	157	123	27
		Maize/Fallow	16	280	0
		Maize/Dolichos	96	364	7
		Maize(exp)/Dolichos	96	364	7
		Maize+Dolichos/Fallow	35	113	18
	CA	Rice/Fallow	54	106	63
		Rice/Dolichos	68	106	63
		Rice/Vetch	134	106	63
		Maize+Dolichos/Fallow	37	178	11
Hillsides	Conventional	Brachiaria	125	0	0
		Cassava	0	30	0
		Groundnut	90	60	0
		Groundnut+Stylo	138	0	0
		Maize	16	280	0
		Maize+Dolichos	43	244	13
		Rice	64	57	24
		Cassava+Brachiaria	125	30	0
	CA	Brachiaria	125	0	0
		Rice	64	149	0
		Groundnut+Stylo	138	0	3
		Maize+Dolichos	44.08	212	17

Appendix 3: Crop production activity outputs (kg/ha) for each period of two-weeks. One crop production activities can produce various outputs, for example, crop production activities with rice produce rice grain, bran and straw. The by-products used as animal feed are also taken into account.

Type of field	Soil management	Crops (+cover crops)		Oct2	Nov1	Nov1	Dec1	Dec2	Jan1	Jan2	Feb1	Feb1	Mar1	Mar2	Apr1	Apr2	May1	May2	Jun1	Jun2	Jul1	Jul2	Aug1	Aug2	Sep1	Sep2	Oct1
Irrigated paddy fields	Conventional	Irrigated rice	Rice												2 450												
			Rice bran												245	245	245	245	245	245	245	245	245	245	245	245	245
			Rice straw												5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000
Poor water control paddy fields	Conventional	Rice/Fallow	Rice														1 600										
			Rice bran														160	160	160	160	160	160	160	160	160	160	160
			Rice straw														5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000
		Rice/Vetch	Rice											1 600													
			Rice bran											160	160	160	160	160	160	160	160	160	160	160	160	160	160
			Rice straw											5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000
			Vetch residue											0	0	0	0	0	476	952	1 430	1 840	2 380	2 920	3 670	4 560	6 800
	CA	Rice/Fallow	Rice											2 500	0	0	0	0	0	0	0	0	0	0	0	0	0
			Rice bran											250	250	250	250	250	250	250	250	250	250	250	250	250	250
			Rice straw											5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000
		Rice/Vetch	Rice											2 500	0	0	0	0	0	0	0	0	0	0	0	0	0
			Rice bran											250	250	250	250	250	250	250	250	250	250	250	250	250	250
			Rice straw											5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000
			Vetch residue											0	0	0	0	0	476	952	1 430	1 840	2 380	2 920	3 670	4 560	6 800
Allluvial soils	Conventional	Rice/Fallow	Rice											1 700	0	0	0	0	0	0	0	0	0	0	0	0	0
			Rice bran											170	170	170	170	170	170	170	170	170	170	170	170	170	303
			Rice straw											5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000
		Rice/Dolichos	Rice											1 700	0	0	0	0	0	0	0	0	0	0	0	0	0
			Rice bran											170	170	170	170	170	170	170	170	170	170	170	170	170	170
			Rice straw											5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000
			Dolichos residue																								5 000
		Rice/Vetch	Rice											1 700													
			Rice bran											170	170	170	170	170	170	170	170	170	170	170	170	170	170
			Rice straw											5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000
			Vetch residue																476	952	1 430	1 840	2 380	2 920	3 670	4 560	6 800
		Maize/Fallow	Maize													2 060											
			Maize stover													3 502	3 502	3 502	3 502	3 502	3 502	3 502	3 502	3 502	3 502	3 502	3 502
		Maize/Dolichos	Maize													2 060											
			Maize + dolichos residue																								6 410
		Maize(exp)/Dolicl	Maize													2 060											
			Stored maize stover													3 502	3 502	3 502	3 502	3 502	3 502	3 502	3 502	3 502	3 502	3 502	3 502
			Dolichos residue																								5 000
		Maize+Dolichos/l	Maize													2 060											
			Maize + dolichos residue													6 410	6 410	6 410	6 410	6 410	6 410	6 410	6 410	6 410	6 410	6 410	6 410
	CA	Rice/Fallow	Rice												1 800												
			Rice bran												180	180	180	180	180	180	180	180	180	180	180	180	180
			Rice straw												5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000
		Rice/Dolichos	Rice												1 800												
			Rice bran												180	180	180	180	180	180	180	180	180	180	180	180	180
			Rice straw												5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000
			Dolichos residue																								5 000
		Rice/Vetch	Rice												1 800												
			Rice bran												180	180	180	180	180	180	180	180	180	180	180	180	180
			Rice straw												5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000
			Vetch residue																476	952	1 430	1 840	2 380	2 920	3 670	4 560	6 800
		Maize+Dolichos/l	Maize													2 060											
			Maize + dolichos residue													6 410	6 410	6 410	6 410	6 410	6 410	6 410	6 410	6 410	6 410	6 410	6 410
Hillsides	Conventional	Brachiaria	Brachiaria								144	216	360	504	648	792	1 008	1 152	1 440	1 656	1 872	2 160	2 520	2 880	3 168	3 384	3 744
		Cassava	Cassava																					4 500			
		Groundnut	Groundnut													1 000											
		Groundnut+Stylo	Groundnut													1 000											
			Stylosanthes													1 342	1 708	1 952	2 440	2 806	3 172	3 660	4 270	4 880	5 368	5 734	6 344
		Maize	Maize													1 600											
			Maize stover													2 720	2 720	2 720	2 720	2 720	2 720	2 720	2 720	2 720	2 720	2 720	2 720
		Maize+Dolichos	Maize													1 600											
			Maize + dolichos residue													6 410	6 410	6 410	6 410	6 410	6 410	6 410	6 410	6 410	6 410	6 410	6 410
		Rice	Rice													1 254											
			Rice bran													125	125	125	125	125	125	125	125	125	125	125	125
			Rice straw													5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000
		Cassava+Brachia	Cassava																					3 500			
			Brachiaria								144	216	360	504	648	792	1 008	1 152	1 440	1 656	1 872	2 160	2 520	2 880	3 168	3 384	3 744
	CA	Brachiaria	Brachiaria	4 032	4 320	4 680	4 896	5 112	5 328	5 544	5 760	5 904	6 120	6 264	6 336	6 480	6 624	6 696	6 768	6 840	6 912	6 984	7 056	7 128	7 128	7 200	7 200
		Rice	Rice												1 394												
			Rice bran												139	139	139	139	139	139	139	139	139	139	139	139	139
			Rice straw												5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000
		Groundnut+Stylo	Groundnut													1 000											
			Stylosanthes													1 342	1 708	1 952	2 440	2 806	3 172	3 660	4 270	4 880	5 368	5 734	6 344
		Maize+Dolichos	Maize													1 600											
			Maize + dolichos residue													6 410	6 410	6 410	6 410	6 410	6 410	6 410	6 410	6 410	6 410	6 410	6 410
		Stylo	Stylosanthes	6 832	7 320	7 930	8 296	8 662	9 028	9 394	9 760	10 004	10 370	10 614	10 736	10 980	11 224	11 346	11 468	11 590	11 712	11 834	11 956	12 078	12 078	12 200	12 200

Appendix 4: Forage and crop residues nutritive values according to the French feed evaluation system INRA (INRA, 2007) system of “unite fourragère lait” (UFL) equivalent to the energy provided by one kg of oats. One UFL corresponds to the Net Energy of 1 kg of standard barley (1700 kcal NE_L/kg DM of feed). PDI: Protein Digested in the Intestine; PDI value measures the sum of absorbed protein supplied by feed undegradable protein and microbial protein.

	Energy (UFL/kg DM)	Protein (g PDI/kg DM)
Vetch residues	0.71	106
Dolichos residues	0.7	90
Maize stover	0.57	29
Maize stover + dolichos residues	0.71	60
Brachiaria	0.6	70
Stylosanthes	0.7	80
Rice bran	0.58	46
Rice straw	0.58	46
Stored maize stover	0.57	29
Cut-grass	0.65	40

Appendix 5: Animal nutritive (energy) requirements, maximum feed intake (kg DM/day), production (milk and manure), and labor needs for the four types of animals (dairy improved breed, dairy Rana breed, zebu female, zebu male) according to their growth or production stage (calf, heifer, milking, dry).

		Dairy improved breed				Dairy Rana breed				Zebu female				Zebu male	
		Calf	Heifer	Dairy cow Milking	Dairy cow Dry	Calf	Heifer	Dairy cow Milking	Dairy cow Dry	Calf	Heifer	Dairy cow Milking	Dairy cow Dry	Young male	Adult male
Weight (kg)		80	180	400	400	50	150	300	300	50	100	180	180	50	250
Energy req. (UFL/day)	Growth	1.7	2.8			1.3	2.4			0.9	2.1			0.9	
	Maintenance			3.2	3.2			2.8	2.8			2.3	2.3		2.8
	Lactation/Work			3.1				1.8				1.8			3.9
	Pregnancy				1.5				1.5				1.5		
Energy req. (g MAD animal/day)	Growth	150	240			120	205			100	180			100	
	Maintenance			245	245			215	215			165	165		100
	Lactation/work			336				192				192			290
	Pregnancy				105				105				105		
Milk production (l/day)				7				4				4			
Maximum feed intake (kg DM/day)		1.7	4.9	10.8	10.8	0.9	3.6	8.1	8.1	0.9	2.3	4.5	4.5	0.9	6.25
Manure Average anual prod. (kg FM)		390	1 850	3 900	3 900	260	1 300	2 600	2 600	100	500	1 000	1 000	200	1 300
Draught power sell (days/animal/period)															2.5
Labor needs (minutes/day)	Breeding	10	12	20	12	10	12	20	12						
	Feeding	1	1.4	2	1.4	1	1.4	2	1.4						
	Milking			15				15							

Appendix 6: model formulation of GANESH

The model formulation of GANESH is presented here. The model can be solved using linear programming (LP) software, but includes integer variables for area resulting in a mixed integer programming (MIP) model.

Sets

Below are presented all the sets and subsets used in the model:

Crop sets

Soil: defines the 4 types of soil. IPF=Irrigated low land paddy field, PWC=Poor water control low land paddy field, AS=Alluvial soil, Hill=Hillsides

Plot: 1, 2, 3, …, 10

Crop: 1, 2, …, 33

CACrop(Crop): 13 CA cropping systems

CVCrop(Crop): 20 conventional cropping systems

CoverCrop(Crop): Cropping systems that produce biomass for user as mulch or fodder

NotCover(Crop): Cropping systems that do not produce biomass

Cover: 1, 2, …, 12 All the levels of soil cover (0%, 10%, 20%, …, 99%)

Time sets

Year: 1, 2 and 3

Period: 1,2, …, 24 one period=15 days=2 weeks

In/Out-put sets

Output: 1=Rice, 2=corn, 3=Cassava tuber, 4=Groundnut, 5=Vicia residues, 6=Dolichos residues, 7=Corn stover, 8=Corn stover+dolichos residues, 9=Brachiaria, 10=Stylosanthes, 11=Rice bran, 12=Rice straw, 13=Stored corn stover, 14=Cut grass

Sold(Output): 4 sold output

Feed(Output): 10 outputs that can be used as animal feed

Forage(Feed): Outputs only used as forage

CoverForage(Feed): Outputs used either as forage or as cover

Input: 1=seeds, 2=manure, 3=pesticides

Animal sets

Animal: Dib=Dairy improved breed, Drb=Dairy rana breed, Zf=Zebu female, Zm=Zebu male

FemaleA(Animal): Female cows

Age: Animal age in number of periods

Zm_Age(Age): Zebu male age

Calv_F_Age(Age): Calving female age

Calv_M_Age(Age): Calving male age

Sold_Age(Age): Sold age

Production: 1=Milk, 2=Manure, 3=Labour

Need: 1=Labor, 2=Energy(UFL), 3=max kg of ingested dry matter(DM), 4=min kg ingested DM, 5=Protein(MAD)

Family sets

Family: Fam=Total family members

Sets Abbreviations

A	=	Animal	DMC	=	CACrop	Pct	=	Production
Age	=	Age	FA	=	FemaleA	Pl	=	Plot
CAg	=	Calv_F_Age	Fam	=	Family	Pl	=	Period
CAg	=	Calv_M_Age	Fd	=	Feed	Sag	=	Sold_Age
Cp	=	Crop	Fg	=	Forage	Sd	=	Sold
CV	=	CVCrop	I	=	Input	Sl	=	Soil
Cv	=	Cover	NCp	=	NotCover	Y	=	Year
CvCp	=	CoverCrop	Nd	=	Need	Zag	=	Zm_Age
CvFg	=	CoverForage	O	=	Output			

Parameters

Below are listed all the parameters used in GANESH:

Family parameters

$FamilyLabor_{Fam}$: Available family labour per period

$Survival_{Fam}$: Survival threshold per year

$Oxherd_{Fam}$: Oxherd costs

$SelfConsumption_{Sd}$: Self-consumed outputs each year

Cropping systems parameters

$TCA_{Pl,Sl}$: List of all the farmer’s plots and surface areas

$Possible_{Cp,Y,Sl}$: All the possible cropping systems by year for each type of soil

$Yield_{Cp,O,P}$: Crops yields for each period

$Labor_{Cp,P}$: Crops required labour per period

$LaborPrice_{P}$: Price of external labour per day for each period

$Weed\_Labor_{Cp,P}$: 1= it is a weeding task, 0=it is not

$Cost_{Cp,I}$: Crops required inputs

$Price_{Sd}$: Price of each sold output

$CassLimit_{Sd}$: Maximum cassava sold per year

Forage parameters

$ForagePrice_{Fd}$: Forage prices

$Forage\_Char_{Fd,Nd}$: Forage characteristics (UFL, and kg DM)

Animal parameters

$I\_Stock_{Age,A}$: Initial herd composition

$Herd\_Need_{Age,Nd,A}$: Herd needs in terms of labour, UFL and DM

$Herd\_Production_{Age,Pct,A}$: Herd productions in terms of labour, manure and milk

$MilkLimit_{P}$: Milk production limit per period

$Production\_Price_{Pct}$: Milk, manure and labour prices

Cover parameters

$Soil\_Cover_{Cv,CvFg}$: Equivalence between cover quantity and cover percentage

$Weed\_Cover_{Cv}$: Labour multiplication factor depending on left cover

$Forage\_Crop_{CvCp,CvFg}$: Determines the kind of forage produced by a crop

Variables

Below are listed all the variables used in the model:

Free variables

$vTotalIncome$: Balance at the end 6 years

$vHerd_{A,Y,P,Age}$: Herd evolution all along the model

$vTot\_Head_{Y,P}$: Herd evolution

$vTot\_Culled\_Animal_{A,Y,P}$: Total number of culled animal

$vFemaleA\_Sold_{A,Y,P}$: Number of sold calves*

$vHerd\_Need_{A,Nd,Y,P}$: Animals needs

$vTot\_Need_{Nd,Y,P}$: Total needs

$vTotFarmForage_{Fd,Y,P,Sl,Pl}$: Cumulated forage exported from the fields every year

$vFarmProduction_{O,Y,P,Sl,Pl}$: Output production every period

$vHerd\_Production_{A,Pct,Y,P}$: Milk, manure and labour production per animal every period

$vTot\_Production_{Pct,Y,P}$: Milk, manure and labour production every period

Binary variables

$vX_{Y,Sl,Pl,Cp,Cv}$: 0=the crop is not selected, 1=the crop is selected

Integer variables

$vExtLabor_{Y,P}$: Number of days of external labour

Positive variables

$vFarmForage_{Fd,A,Y,P,Sl,Pl}$: Forage exported from the fields to feed animals

$vExtForage_{Fd,A,Y,P}$: Bought forage for animal

$vExpForage_{Fd,Y,P,Sl,Pl}$: Exported forage to be stored

$vStockForage_{Fd,A,Y,P,Sl,Pl}$: Forage exported from the stock to feed animals

$vStoredForage_{Fd,Y,P,Sl,Pl}$: Stored forage evolution

$vCoverIn24_{Y,Sl,Pl,CvFg}$: Biomass left on the field at the period 24

$vMilkLimit_{Y,P}$: Limited quantities of sold milk

$vCassLimit_{Y,P,Sl,Pl}$: Limited quantities of cassava roots sold

Equations

This section presents the equations used for formulating the constraints, the auxiliary variables, the balances and the objective functions:

Farm plan equations

One crop per plot per year:

Each year, a plot cannot contain more than one crop

$$\sum_{Cp,Cv} vX_{Y,Sl,Pl,Cp,Cv} \times Possible_{Cp,Y,Sl} \leq 1 \; for \; hills$$

$$\sum_{Cp,Cv} vX_{Y,Sl,Pl,Cp,Cv} \times Possible_{Cp,Y,Sl} = 1 \; for \; other \; soils$$

$$\sum_{Cp,Cv} vX_{Y,Sl,Pl,Cp,Cv} \leq 1 \; internal \; rule \; because \; of \; the \; parameter \; "Possible"$$

Crop production equations

Plot periodic production:

Outputs produced on each crop every period (except for cassava).

$$\sum_{Cp,Cv} vX_{Y,Sl,Pl,Cp,Cv} \times Possible_{Cp,Y,Sl} \times Yield_{Cp,O,P} \times TCA_{Pl,Sl}$$
$$= vFarmProduction_{O,Y,P,Sl,Pl}$$

Cassava limitation

$$(vX_{Y,Sl,Pl,Cp,Cv} \times Possible_{Cp,Y,Sl} \times Yield_{Cp,3,P} \times TCA_{Pl,Sl}) - vCassLimit_{Y,P,Sl,Pl}$$
$$= vFarmProduction_{3,Y,P,Sl,Pl}$$

$$\sum_{P,Sl,Pl} vFarmProduction_{3,Y,P,Sl,Pl} - SelfConsumption_3 \leq CassLimit_3$$

<u>Succession rules equations</u>

CA crop after biomass:

A CA crop can only follow a crop that produces a certain amount of biomass (user parameter)

$$\sum_{Cv,CvCp} vX_{Y,Sl,Pl,CvCp,Cv} - \sum_{Cv,DMC} vX_{Y+1,Sl,Pl,DMC,Cv} \geq -0.5 \ if \ cover$$
$$\geq 4 \ for \ a \ minimum \ of \ 30\%$$

Forced minimum cover:

Minimum cover left on CA crops

$$\sum_{Cv,DMC} vX_{Y,Sl,Pl,DMC,Cv} = 0 \ if \ cover < 2 \ for \ a \ minimum \ of \ 10\%$$

Stylosanthes and brachiaria rules:

Pure stylo/brach can only follow a stylo/brach system or itself

$$\sum_{Cv} vX_{Y,Sl,Pl,CvCp,Cv} - vX_{Y+1,Sl,Pl,25/29,Cv} = 0 \ if \ Crop = Stylo \ or \ brachiaria \ system$$

Constant cover:

The cover %age remains constant every year on the same plot

$$\sum_{CvCp} vX_{Y,Sl,Pl,CvCp,Cv} - \sum_{CvCp} vX_{Y+1,Sl,Pl,CvCp,Cv} \leq 0$$

Automatic cover attribution:

Cropping systems that don't produce biomass have a cover=1

$$\sum_{Y,Sl,Pl,NCp,Cv} vX_{Y,Sl,Pl,NCp,Cv} = 0 \; if \; cover > 1$$

<u>Herd evolution equations</u>

Initial herd composition:

The initial stock is determine by user

$$vHerd_{A,1,1,Age} = I\_Stock_{Age,A}$$

Herd evolution:

The herd composition evolves every period

$$vTot\_Head_{Y,P} = \sum_{A,Age} vHerd_{A,Y,P,Age}$$

Age evolution for each period

$$vHerd_{A,Y,1,Age} = vHerd_{A,Y-1,24,Age-1} \; if \; period = 1$$

$$vHerd_{A,Y,P,Age} = vHerd_{A,Y,P-1,Age-1} \; if \; period \neq 1$$

Number of culled animals every period

$$vTot\_Culled\_Animal_{A,Y,1} = vHerd_{A,Y-1,24,culled\;age} \; if \; period = 1$$

$$vTot\_Culled\_Animal_{A,Y,P} = vHerd_{A,Y,P-1,culled\;age} \; if \; period \neq 1$$

Number of sold calves every period

$$vFemaleA\_Sold_{FA,Y,P} = \sum_{CAg} vHerd_{FA,Y,P,CAg}$$

<u>Animal production equations</u>

Herd production:

Every period, animals produce milk, manure and labour

$$vHerd\_Production_{A,Pct,Y,P} = \sum_{Age} vHerd_{A,Y,P,Age} \times Herd\_Production_{Age,Pct,A}$$

Total animal production:

Every period farm produces milk, manure and labour

$$vTot\_Production_{Pct,Y,P} = \sum_{A} vHerd\_Production_{A,Pct,Y,P} \; except \; for \; milk$$

Sold milk limitation every period

$$vTot\_Production_{1,Y,P} = \sum_{A} vHerd\_Production_{A,1,Y,P} - vMilkLimit_{Y,P}$$

$$vTot\_Production_{1,Y,P} \leq MilkLimit_{P}$$

Animal needs equations

Animal needs:

Every period animals needs UFL, MAD, labour and certain quantity of forage

$$vHerd\_Need_{A,Nd,Y,P} = \sum_{Age} vHerd_{A,Y,P,Age} \times Herd\_Need_{Age,Nd,A}$$

$$vTot\_Need_{Nd,Y,P} = \sum_{A} vHerd\_Need_{A,Nd,Y,P}$$

$$\geq vHerd\_Need_{A,Nd,Y,P} \; for \; UFL \; and \; MAD$$

Ration composition:

The ration composition has to fulfil the animal needs

$$\sum_{Fd,Sl,Pl} vFarmForage_{Fd,A,Y,P,Sl,Pl} \times Forage\_Char_{Fd,Nd}$$

$$+ \sum_{Fd,Sl,Pl} vStockForage_{Fd,A,Y,P,Sl,Pl} \times Forage\_Char_{Fd,Nd}$$

$+vExtForage_{Fd,A,Y,P}$

$= vHerd\_Need_{A,Nd,Y,P}\ for\ UFL$

$\geq vHerd\_Need_{A,Nd,Y,P}\ for\ mininum\ kg\ of\ ingested\ DM$

$\leq vHerd\_Need_{A,Nd,Y,P}\ for\ maximum\ kg\ of\ ingested\ DM$

Forage evolution equations

Initial forage stock:

At the beginning, the stock is empty

$$vStockForage_{Fd,A,1,1,Sl,Pl} + vStoredForage_{Fd,1,1,Sl,Pl} = 0$$

Stored forage evolution:

The stock evolution depends on the amount of stored/given forage

$$vStoredForage_{Fd,Y,P-1,Sl,Pl} + vExpForage_{Fd,Y,P-1,Sl,Pl} - \sum_{A} vStockForage_{Fd,A,Y,P-1,Sl,Pl}$$

$$= vStoredForage_{Fd,Y,P,Sl,Pl}\ if\ period \neq 1$$

$$vStoredForage_{Fd,Y-1,24,Sl,Pl} + vExpForage_{Fd,Y-1,24,Sl,Pl} - \sum_{A} vStockForage_{Fd,A,Y-1,24,Sl,Pl}$$

$$= vStoredForage_{Fd,Y,1,Sl,Pl}\ if\ period = 1$$

$$vStoredForage_{Fd,3,24,Sl,Pl} \geq \sum_{A} vStockForage_{Fd,A,3,24,Sl,Pl}\ \ for\ the\ last\ period$$

Storage duration:

Forages cannot be stored longer than one year

$$\sum_{A,P,Sl,Pl} vStockForage_{Fd,A,Y,P,Sl,Pl} = \sum_{Sl,Pl} vStoredForage_{Fd,Y,1,Sl,Pl}$$

Given forage:

Total given forage directly from the plots. Every year, it starts at 0

$$vTotFarmForage_{Fd,Y,P-1,Sl,Pl} + vExpForage_{Fd,Y,P-1,Sl,Pl} + \sum_{A} vFarmForage_{Fd,A,Y,P-1,Sl,Pl} = vTotFarmForage_{Fd,Y,P,Sl,Pl}$$

$$vTotFarmForage_{Fd,Y,1,Sl,Pl} = 0 \; if \; period = 1$$

Available forage:

Maximum exportable forage from field each period

$$vExpForage_{Fd,Y,P,Sl,Pl} + \sum_{A} vFarmForage_{Fd,A,Y,P,Sl,Pl} \leq vFarmProduction_{Fd,Y,P,Sl,Pl} - vTotFarmForage_{Fd,Y,P,Sl,Pl}$$

Cover management equations

Cover left:

Quantity of biomass left on period 24

$$vFarmProduction_{Fd,Y,24,Sl,Pl} - vTotFarmForage_{Fd,Y,24,Sl,Pl} - vExpForage_{Fd,Y,24,Sl,Pl} - \sum_{A} vFarmForage_{Fd,A,Y,24,Sl,Pl} = vCoverIn24_{Y,Sl,Pl,CvFg}$$

Cover rate conversion:

Conversion from kg to %age of cover

$$\sum_{CvCp,CvFg,Cv} vX_{Y,Sl,Pl,CvCp,Cv} \times TCA_{Pl,Sl} \times Soil\_Cover_{Cv,CvFg} \times Forage\_Crop_{CvCp,CvFg} \times 1.0001 \leq \sum_{CvFg} vCoverIn24_{Y,Sl,Pl,CvFg} \; lower \; limit$$

$$\sum_{CvCp,CvFg,Cv} vX_{Y,Sl,Pl,CvCp,Cv} \times TCA_{Pl,Sl} \times Soil\_Cover_{Cv+1,CvFg} \times Forage\_Crop_{CvCp,CvFg} \geq \sum_{CvFg} vCoverIn24_{Y,Sl,Pl,CvFg} \; upper \; limit$$

Labour equations

Total labour:

Total farm labour is split between family and external labour

$$\sum_{Sl,Pl,Cp,Cv} vX_{1,Sl,Pl,Cp,Cv} \times Labour_{Cp,P} \times TCA_{Pl,Sl} + vTot\_Need_{1,1,P}$$
$$+ \sum_{Fd,A,Sl,Pl} vFarmForage_{Fd,A,1,P,Sl,Pl} \times Forage\_Char_{Fd,Nd}$$
$$+ \sum_{Fd,Sl,Pl} vExpForage_{Fd,1,P,Sl,Pl} \times Forage\_Char_{Fd,Nd}$$
$$\leq vExtLabour_{1,P} + FamilyLabour_{Fam}\ for\ year = 1$$

$$\sum_{Sl,Pl,Cp,Cv} vX_{Y,Sl,Pl,Cp,Cv} \times Labour_{Cp,P} \times TCA_{Pl,Sl} + vTot\_Need_{1,Y,P}$$
$$+ \sum_{Sl,Pl,Cp,Cv} vX_{Y,Sl,Pl,Cp,Cv} \times Labour_{Cp,P} \times TCA_{Pl,Sl} \times Weed\_Labour_{Cp,P} \times Weed\_Cover_{Cv}$$
$$+ \sum_{Fd,A,Sl,Pl} vFarmForage_{Fd,A,Y,P,Sl,Pl} \times Forage\_Char_{Fd,Nd}$$
$$+ \sum_{Fd,Sl,Pl} vExpForage_{Fd,Y,P,Sl,Pl} \times Forage\_Char_{Fd,Nd}$$
$$\leq vExtLabour_{Y,P} + FamilyLabour_{Fam}\ for\ the\ other\ years$$

Family needs equations

Self-consumption:

The family consumes on-farm produced outputs

$$\sum_{P,Sl,Pl} vFarmProduction_{Sd,Y,P,Sl,Pl} \geq vFarmProduction_{O,Y,P,Sl,Pl}$$

Survival threshold:

Every year, the income has to fulfill the minimum for living

$$\sum_{Sd,P,Sl,Pl} vFarmProduction_{Sd,Y,P,Sl,Pl} \times Price_{Sd}$$
$$- \sum_{Sl,Pl,Cp,Cv,I} vX_{Y,Sl,Pl,Cp,Cv} \times Cost_{Cp,I} \times TCA_{Pl,Sl}$$
$$- \sum_{Fd,A,P} vExtForage_{Fd,A,Y,P} \times ForagePrice_{Fd}$$
$$+ \sum_{Pct,P} vTot\_Production_{Pct,Y,P} \times Production\_Price_{Pct}$$
$$- \sum_{P} vExtLabor_{Y,P} \times LabourPrice_{P}$$
$$-Oxherd_{Fam} + \sum_{A,P} vFemaleA\_Sold_{A,Y,P} \times 200 = Survival_{Fam}$$

<u>Objective function: Final Income</u>

This is the function to optimize

$$\sum_{Sd,Y,P,Sl,Pl} vFarmProduction_{Sd,Y,P,Sl,Pl} \times Price_{Sd}$$
$$- \sum_{Y,Sl,Pl,Cp,Cv,I} vX_{Y,Sl,Pl,Cp,Cv} \times Cost_{Cp,I} \times TCA_{Pl,Sl}$$
$$- \sum_{Fd,A,Y,P} vExtForage_{Fd,A,Y,P} \times ForagePrice_{Fd} - \sum_{Sd} SelfConsumption_{Sd}$$
$$\times Price_{Sd} \times 3$$
$$+ \sum_{Pct,Y,P} vTot\_Production_{Pct,Y,P} \times Production\_Price_{Pct}$$
$$- \sum_{Y,P} vExtLabour_{Y,P} \times LabourPrice_{P}$$
$$-(Oxherd_{Fam} \times 3) + \sum_{A,Y,P} vFemaleA\_Sold_{A,Y,P} \times 200$$
$$= vTotalIncome$$

Summary

Conservation Agriculture (CA) is defined by three main principles: direct seeding, permanent soil cover, and crop diversification. CA is promoted as a promising technology in Africa, but to date, the extent of land under CA that fully complies with the three above principles is very limited. CA has both short and long term effects on crop productivity and sustainability as it modifies different agroecological functions. These functions are related to the quantity of biomass produced by the crop and cover crop that is left on the ground as mulch. One of the main challenges in designing CA for smallholder farming systems in developing countries is competing uses of biomass, in particular for livestock feeding. The difficulty is thus linking the efficiency of agroecological functions to differing amounts of biomass to be exported, and evaluating the performance of cropping systems at farm level, i.e. the level the at which decisions are made.

Our results showed that the application of the first CA principle (direct seeding) alone did not have a significant impact on cotton production in the Far North province of Cameroon as yields obtained under no till with or without mulch were not different from those with tillage (Chapter 2). The second principle (soil cover) produced higher yields with the no till system with mulch than without mulch. In the two provinces of Cameroon in which the tillage, no tillage, and no tillage with mulch systems were compared, there was a difference in soil cover, in the number of herbicide application, ridging, and the amount of nitrogen fertilizer used by farmers. In Far North Province, there was also a difference in the number of weedings and the date of the first weeding. In Far North Province, cotton yields were 12% lower with tillage and 24% lower with no tillage with no mulch than with no tillage with mulch. Cotton yields were regressed on crop husbandry indicators and the amount of inputs used. After manual backward removal in a multiple linear regression, no parameters were found to significantly influence yield for tillage, only one parameter for no tillage, the number of herbicide application used at sowing, and three parameters for

no tillage with mulch: difference between heavy clay and silty loam, application of NPK fertilizer, and sowing date. In North Province, no difference in cotton yield was observed between the three treatments. The flowering period was longer with no tillage with mulch than with no tillage in the Far North and North Provinces and with no tillage with mulch than with tillage in North Province, respectively 13, 9 and 8 days. The last principle (crop diversity) was implemented by planting a cover crop with cereals that doubled the quantity of aboveground biomass produced. The cereal management systems compared were conventional management and CA consisting in the production of mulch using cover crops (*Brachiaria ruziziensis, Crotalaria retusa, Dolichos lablab, Mucuna pruriens,* and *Vigna unguiculata*) intercropped with the cereal. In Far North Province, up to 9.7 t ha^{-1} of vegetative biomass was produced in CA plots with sorghum and cover crops compared to 4.8 t ha^{-1} for sorghum alone in conventional plots. In North Province maize + a cover crop produced up to 5.2 t ha^{-1} of biomass compared with 2.5 t ha^{-1} for maize alone. In both provinces, the cereal grain yields in CA plots were the same as or higher than yields in conventional plots. In 18 fields in Far North Province, the mulch remaining the year after sorghum + *B. ruziziensis* ranged between 3 t ha^{-1} and 5 t ha^{-1}. Although we found that CA can have benefits at field level, our results indicated that further studies are needed to assess the suitability of CA at farm and village levels.

The second principle of CA (soil cover) is closely linked with the third principle (crop diversity) (Chapter 3). The soil cover in rice fields grown under CA in the Alaotra region of Madagascar can vary considerably. Three different kinds of cropping systems were investigated in 91 farmers' fields. The first two cropping sequences were applied in hillside fields: (i) maize + pulse (*Vigna unguiculata* or *Dolichos lablab*) in year 1, followed by upland rice in year 2; (ii) the second crop sequence included several years of *Stylosanthes guianensis* followed by upland rice; (iii) the third crop sequence was applied in lowland paddy fields: *Vicia villosa* or *D. lablab*, followed by rice in the same year and the same sequence was repeated every year. The biomass available prior to rice sowing ranged from 3.6 t ha^{-1} with *S. guianensis* to 7.3 t ha^{-1} with *V. villosa*.

We investigated the relationship between the quantity of biomass produced and that left on the soil as mulch and the soil cover this provides for a range of different crops and cover crops. The relationship between the quantity of mulch (M) and soil cover (C) was measured using digital imaging and was well described by the following equation: $C = 1 - \exp^{(-Am \times M)}$, where Am is an area-to-mass ratio with $R^2 > 0.99$ in all cases.

We used these relationships to explore the variability of soil cover observed in farmers' fields. The calculated average soil cover ranged from 56% for maize + *V. unguiculata* to to 97% for maize + *V. villosa*. Of course, whether the different agroecological functions of CA can be fulfilled depends on the amount of biomass produced, residue management, and the resulting soil cover. To maintain 90% soil cover at rice sowing, the average amount of biomass of *V. villosa* that could be removed was at least 3 t ha^{-1} for three quarters of the fields. Our study showed that under farmers' conditions in Madagascar, the production and conservation of biomass is not always sufficient to fulfill all the agroecological functions of mulch. Furthermore, the thresholds vary depending on the function concerned. For example, partial removal of biomass to be used as forage may not reduce the effectiveness of the mulch in erosion control but the same amount of removal may markedly reduce its effectiveness in weed control.

As the balance of potential benefits derived from removal of biomass for feed varies depending on farm constraints and goals, we modelled the potential benefits of aboveground biomass exported to feed cattle at farm level (Chapter 4). We used Malagasy farms of different sizes to explore the relationships between raising dairy cows and CA. Our aim was to explore trade-offs and synergies between combinations of CA practices (different amounts of biomass exported) and the size of dairy cow herds (with animal production depending on biomass for feed). We applied constraints on the minimum soil cover (from 30% to 95) to be kept in CA fields at the end of each year.. We simulated two milk market scenarios: a small milk market with a low price for forage and an open milk market with a higher price for forage. Three kinds of farms were simulated: medium-sized farms with mostly hillside fields, medium-sized farms with mostly paddy fields, and small farms with only hillside fields. Changing the percentage soil cover to be retained in CA plots did not significantly modify total farm net income, which was more influenced by the characteristics of the milk market. In the case of a limited milk market, it was not profitable for a farmer to have more than seven cows because the expenses involved were not compensated for by the sale of animal products. In most of the situations simulated with more than six/seven cows, the model chose to introduce CA cropping systems producing more forage on the hillsides if we allowed the model to implement CA with only 30% of soil cover. Conversely when this constraint was set to 95%, the model chose not to implement CA on hillsides. In all the situations simulated with the maximum number of cows (12) it was possible to keep at least 50% of soil cover on 80% of the hillside fields. On the other hand, it was impossible to keep 95% of soil cover when forage fetched a high price. Overall, CA systems can be profitable for dairy cow farmers due to the forage produced, although the milk market and hence the value of biomass for forage, has a major influence on the way CA can be implemented at field level. Even with a limited number of possible cropping activities (28) many different combinations of cropping systems are possible. In fact the total number of possible cropping activities even for one kind of field is very large when all possible crops and cover crops that can be grown are taken into consideration.

This led us to explore the whole range of possible cropping systems for known field situations in Chapter 5. In this chapter the focus was on the third principle of CA (crop diversity). Our aim was to propose a method for designing CA cropping systems suitable for each of these situations. We formalized the hypothesis underlying the design, which was based on field characterisation, the choice of a cover crop for different types of fields, possible combinations of intercrops and crop sequences, and cover crops. This work demonstrates that even after applying agronomic rules, from a biophysical perspective, the number of feasible cropping systems is still large. The number of cropping systems was then reduced to account for farmers' preferences, goals, and constraints at farm level. The evaluation of cropping systems designed *per se* without reference to farm types, is not relevant for the real farming situation. Following the same reasoning and for each type of farm, the suitability of a cropping system should be considered in relation with other activities (crop, animal production and off-farm activities).

If we assume that, in developing countries, the main factor determining the success of CA is competition for plant biomass for use as mulch or for cattle feed, then the benefits of leaving mulch on the soil surface have to be balanced against the use of biomass as feed. This balancing is done at farm level. The relationships between the quantity of mulch, the soil cover, and of the fulfilment of agroecological functions have only been partially characterized in developing countries. Further research is required to understand these relationships. Quantitative assessments are needed for new more appropriate systems to be designed. Such assessments are also needed to provide quantitative tools for development agents and for farmers on the trade-offs related to the use of biomass.

We also call for a more rigorous description of cropping systems, technical management, residue management, and quantification of biomass production and of the mulch cover when reporting experiences concerning CA. This would give the scientific community a clearer view of the impacts and limitations of CA for smallholders as a function of different technical management options. In this way, we hope that the debate around the suitability of CA for developing countries could be based on shared views of the positive impacts and limitations rather than on ideological positions.

Samenvatting

Conservation agriculture (CA) kent drie kernbeginselen: minimale bodemverstoring (oftewel geen grondbewerking en direct zaaien in smalle sleuven), permanente grondbedekking en diversificatie van gewassen. CA wordt gezien als een veelbelovende technologie voor Afrika. Echter, tot op heden is het landoppervlak waarop CA volledig volgens de drie bovenstaande beginselen wordt toegepast beperkt. CA heeft zowel korte als lange termijn effecten op de productiviteit en duurzaamheid van de teelt doordat het verschillende agro-ecologische functies modificeerd. Deze functies zijn gerelateerd aan de hoeveelheid biomassa die wordt geproduceerd door het gewas zelf en door de grondbedekker die op het veld achterblijft als mulch. Een van de belangrijkste uitdagingen bij het ontwikkelen van CA voor kleinschalige landbouwsystemen in ontwikkelingslanden is dat biomassa ook voor andere concurrerende doeleinden wordt gebruikt, zoals veevoeder. De moeilijkheid ligt dus in het leggen van verbanden tussen de efficientie van agro-ecologische functies en verschillende niveaus van biomassa ‘uitval’, en in het beoordelen van de prestaties van teeltsystemen op bedrijfsniveau, oftewel het niveau waar de beslissingen worden genomen.

Onze bevindingen wezen uit dat toepassing van slechts het eerste CA-beginsel (direct zaaien) geen significante invloed had op de katoenproductie in de extreem-noordelijke provincie (‘Far North Province”) van Kameroen: de opbgrensten met en zonder mulch waren niet verschillend ongeacht het wel of niet bewerken van de grond (hoofdstuk 2). Het tweede beginsel (grondbedekking) leidde tot hogere opbrengsten zonder grondbewerking maar met mulch vergeleken met wanneer geen mulch werd toegepast. In de twee Kameroenese provincies waar de drie varianten werden vergeleken, namelijk ploegen, geen grondbewerking en geen grondbewerking met verschillende mulchsystemen, was er een verschil in grondbedekking, het aantal herbicide toepassingen, aanaarding en de hoeveelheid gebruikte stikstofkunstmest. In de extreem-noordelijke provincie varieerde ook het aantal keren dat onkruid gewied werd en het tijdstip waarop de boer voor het eerst wiedde. In deze provincie waren de katoenopbrengsten 12% lager wanneer eerst werd geploegd, en 24% lager zonder ploegen en zonder mulch, vergeleken met situaties waarin de grond niet werd bewerkt maar wel werd gemulcht. We onderzochten de invloed van verschillende indicatoren voor gewasgerelateerde parktijken en de hoeveelheid gebruikte inputs op katoenopbrengsten. Na het één voor één handmatig verwijderen van niet-significante parameters in een meervoudige lineaire regressie, bleek dat geen enkele parameter de opbrengst bij eerst ploegen significant beïnvloedde, en slechts één parameter die bij geen grondbewerking - namelijk het aantal herbicide-toepassingen tijdens het zaaien. Bij geen grondbewerking maar met mulch, vonden we drie parameters die de opbrengst significant beinvloedden: de grondsoort - zware klei of leem, het gebruik van NPK kunstmest en de zaaitijd (datum). In de noordelijke provincie (“North Province”), vonden we geen verschil in katoenopbrengst tussen deze drie behandelmethoden. In de extreem-noordelijke en noordelijke provincies was de bloeiperiode langer bij geen grondbewerking met mulch dan bij geen grondbewerking alleen, respectievelijk 13 en 9 dagen. In de noordelijke provincie was de bloeiperiode ook langer bij geen grondbewerking met mulch dan bij ploegen alleen, respectivelijk 13 en 8 dagen. Het derde beginsel van CA, gewasdiversificatie, werd toegepast door middel van *intercropping.* Hierbij werd een grondbedekkend gewas afgewisseld met rijen van het hoofdgewas, in dit geval granen. In deze studie werden conventionele graanteeltsystemen vergeleken met CA waarbij grondbedekkende gewassen zoals *Crotalaria Retusa, Dolichos Lablab, Mucuna Pruriens* en *Vigna Unguiculata* werden geplant tussen de granen. In de extreem-noordelijke provincie leidde dit tot verdubbeling van de hoeveel geproduceerde bovengrondse biomassa. Op de CA-percelen waar sorghum samen met een grondbedekker geplant werd, was de opbrengst aan vegetatieve biomassa 9.7 ton per hectare, in vergelijking met 4.8 ton voor alleen sorghum op conventionele percelen. In de noordelijke provincie bracht het planten van maïs met grondbedekkers 5.2 ton biomassa per hectare op, vergeleken met slechts 2.5 ton op percelen waar enkel maïs stond. In beide provincies was de graanopbrengst op de CA-percelen hetzelfde of hoger dan op de conventionele percelen. Daarnaast bleef op 18 percelen in het extreme noorden, een jaar na het telen van sorghum samen met *B. Ruziziensis,* tussen de 3 en 5 ton per hectare mulch liggen. Hoewel we ondervonden dat CA voordelen biedt op veldniveau, maken deze resultaten ook duidelijk dat meer onderzoek nodig is naar de verdiensten van CA op de schaal van de boerderij of het dorp.

Het tweede beginsel van CA (grondbedekking) is nauw verwant aan het derde, diversificatie van gewassen (hoofdstuk 3). De mate van grondbedekking in de rijstvelden van één van de grootste rijstproducerende regio's van Madagaskar, de Alaotra regio, varieert aanzienlijk. Drie verschillende teeltsystemen werden onderzocht op 91 velden; twee systemen werden toegepast op velden op de hellingen en één in de laagland rijstvelden. Op de hellingen waren dit : (i) maïs samen met peulvruchten (*Vigna Unguiculata* of *Dolichos Lablab*) in het eerste jaar gevolgd door hoogland rijst in het tweede jaar, (ii) *Stylosanthes guianensis* gedurende meerdere jaren, met daarna hoogland rijst. In de laagland rijstvelden werd (iii) *Vicia villosa* of *D. Lablab* gevolgd door rijst in hetzelfde jaar, en dit gedurende een aantal achtereenvolgende jaren herhaald. De biomassa voordat rijst gezaaid werd was 3.6 ton per hectare met *S. Guianensis* en 7.3 ton met *V. Villosa.*

We onderzochten de verhouding tussende hoeveel geproduceerde biomassa, de hoeveelheid die op het veld achter werd gelaten als mulch en de mate van grondbedekking dat dit opleverde voor verschillende graan- en grondbedekkende gewassen. De verhoudingen tussen de hoeveelheid mulch (*M*) en de mate van grondbedekking (*C*=”Coverage”) werd gemeten met “digital imaging” en werd goed beschreven met de volgende vergelijking: $C = 1 - \exp^{(-Am \times M)}$, waarbij *Am* de oppervlakte-tot-massa (*Area-to-mass)* verhouding is, met in alle gevallen $R^2 > 0.99$.

Aan de hand van deze verhoudingen onderzochten we de geobserveerde variabiliteit in mate van grondbedekking tussen verschillende percelen. De gemiddelde bedekking varieerde tussen 56% en 97% voor maïs samen met *V. Unguiculata* and *V. Villosa*, respectievelijk. In hoeverre de agro-ecologische functies van CA vervuld kunnen worden hangt natuurlijk af van de hoeveelheid geproduceerde biomassa, het beheer van gewasresiduëen en de daaruit voortvloeiende bedekking van de grond. Om een grondbedekking van 90% te behouden tijdens het rijstzaaien kon in drie kwart van de velden gemiddeld 3 ton per hectare aan *V. Villosa* biomassa worden verwijderd. Ons onderzoek laat zien dat onder de lokale omstandigheden voor boeren in Madagaskar, de productie en het behoud van biomassa niet altijd voldoende zijn om alle agro-ecologische functies van mulch te vervullen. Bovendien varieren de drempelwaardes voor biomassa afhankelijk van de betreffende functie. Bijvoorbeeld, een gedeeltelijke verwijdering van biomassa voor veevoeder hoeft niet per se een negatieve invloed te hebben op de effectiviteit van mulch in erosiebestrijding. Echter, eenzelfde hoeveelheid verwijderde biomassa kan de effectiviteit van mulch voor onkruidbeheersing wél aanzienlijk aantasten.

Aangezien de potentiële voordelen van het gebruik van biomassa als veevoeder varieeren naar gelang de beperkingen en doelen van het bedrijf, hebben we deze gemodelleerd op bedrijfschaal (Hoofdstuk 4). Hiervoor gebruikten we boerenbedrijfjes van verschillende groottes in Madagaskar. We wilden onderzoeken hoe verschillende combinaties van CA-praktijken (met verschillende mates van uitval van biomassa) zich verhouden tot de grootte van kuddes melkvee (waarbij dierlijke productie afhankelijk was van biomassa als veevoer). We bepaalden verschillende minimale percentages grondbedekking (van 30% tot 95%) die aan het einde van ieder jaar op de CA-velden moesten worden aangehouden. Daarnaast simuleerden we twee scenario's voor het vermarkten van melk: een beperkte melkmarkt met lage prijzen voor veevoeder, en een open melkmarkt met een hogere prijs voor veevoeder. Drie soorten boerenbedrijven werden gesimuleerd: middelgrote bedrijven op heuvelachtig terrein, middelgrote bedrijven met voornamelijk laaglandrijstvelden en kleine boerderijen met alleen velden op hellingen. De conclusie was dat het percentage te behouden grondbedekking in CA percelen geen invloed had op het totale netto bedrijfsinkomen. Dit inkomen werd meer beïnvloed door het type melkmarkt. In het geval van een gelimiteerde markt bleek het voor een boer niet rendabel om meer dan zeven koeien te hebben, omdat de daarbij gemoeide kosten niet werden gecompenseerd door de verkoop van melk. In de meeste situaties waarbij meer dan zes/zeven koeien werd gesimuleerd, koos het model voor de introductie van CA-teeltsystemen die meer veevoeder op de hellingen genereerden mits we toestemming gaven voor slechts 30% grondbedekking. Wanneer we een minimum percentage van 95% oplegden, zag het model af van CA op hellingen. In alle simulaties met het maximaal aantal koeien (12) bleek het mogelijk om op 80% van de hellingvelden minstens 50% grondbedekking te behouden. Anderzijds was het onmogelijk om 95% grondbedekking te behouden wanneer voedergewassen hoge prijzen haalden. Al met al kunnen CA systemen rendabel zijn voor melkveehouders, met name door het produceren van veevoeder, hoewel de melkmarkt en dus de waarde van biomassa voor voer, een sterke weerslag heeft op de manier waarop CA kan worden geimplementeerd op veldniveau. Zelfs met een beperkt aantal mogelijke teeltactiviteiten (28), zijn er vele mogelijke combinaties van teeltsystemen. Alle hoofd- en grondbedekkendegewassen in aanmerking nemende, levert dit talrijke mogelijke combinaties van teeltactiviteiten op, zelfs voor maar één type veld.

Dit bracht ons ertoe om in Hoofdstuk 5 het gehele scala aan mogelijke teeltsysteem te verkennen voor bekende veldsituaties. In dit hoofdstuk ligt de nadruk op het derde beginsel van CA; diversiteit van gewassen. Ons doel was om een methode te ontwikkelen om CA-teeltsystemen te ontwikkelen die geschikt waren voor elk van deze situaties. We formaliseerden de hypothese die aan het ontwerp ten grondslag lag. Deze was gebaseerd op veldkarakterisatie, de keuze van een grondbedekkend gewas voor verschillende veldtypes (hellingen, laagland), mogelijke combinaties van gewassen en gewasvolgordes, en grondbedekkende gewassen. Deze activiteit toonde aan dat zelfs na het toepassen van agronomische regels het aantal haalbare teeltsystemen, vanuit biofysisch perspectief, nog steeds erg groot is. Daarop hebben we het aantal teeltsystemen verminderd naar gelang de voorkeur van boeren, alsmede naar gelang hun bedrijfsdoelstellingen en -

beperkingen. Immers, de evaluatie van teeltsystemen zonder referentie naar bedrijfstype is niet relevant voor echte boerenbedrijfssituaties. Vanuit dezelfde redenering, en voor elk type bedrijf, moet de geschiktheid van een teeltsysteem worden overwogen in relatie tot de overige activiteiten van de kleine boer (teelt-, veehouderij en niet-agrarische activiteiten).

Als we aannemen dat concurrerend gebruik vanplantaardige biomassa als mulch en als veevoeder de belangrijkste factor voor het wel of niet slagen van *Conservation Agriculture* is in ontwikkelingslanden, dan moeten we de voordelen van het gebruik van mulch als grondbedekking afgewegen tegen het gebruik ervan als veevoeder. Deze afweging wordt gemaakt op bedrijfsniveau. De verhoudingen tussen de hoeveelheid mulch, de bedekking van de grond, en het vervullen van agro-ecologische functies zijn nog deels onderbelicht in ontwikkelingslanden. Om deze verhoudingen beter te begrijpen is meer onderzoek nodig. Kwantitatieve evaluaties zijn nodig om geschikte en beter aangepaste teeltsystemen te kunnen ontwerpen. Zulke evaluaties zijn tevens nodig om aan ontwikkelingswerkers en boeren kwantitatieve meetinstrumenten te leveren die de trade-offs rond het gebruik van biomassa duidelijker in kaart te brengen.

We roepen tevens op tot meer diepgaande beschrijvingen van teeltsystemen, technisch management, het beheer van gewasresiduëen en de kwantificatie van biomassaproductie en van de mulchbedekking bij het rapporteren van ervaringen met CA. Dit zou de wetenschappelijke gemeenschap een duidelijker beeld verschaffen van zowel de impacts en beperkingen van CA voor kleine boeren, als een functie van verschillende technische management opties. Hierdoor hopen we dat het debat rond de geschiktheid van CA voor ontwikkelingslanden meer gestoeld zal zijn op gedeelde opvattingen over de meerwaardes en beperkingen van CA, in plaats van op ideologische posities.

Résumé

L’agriculture de conservation (AC) est définie par trois principes : semis direct, couverture organique permanente du sol et diversification végétale. L’AC impacte différentes fonctions agro-écologiques des systèmes de culture, elle a à la fois des effets à court et à long terme sur la productivité et la durabilité des cultures. Ces effets sont notamment liés à la quantité de biomasse produite et laissée sur le sol par les cultures et les plantes de couverture. La compétition pour cette biomasse, en particulier pour l’alimentation des animaux, constitue l’une des principales données à prendre en compte dans la construction de nouveaux systèmes de culture. Toutefois, il est encore difficile de lier l’efficacité des fonctions agro-écologiques à des niveaux d’exportation de la biomasse.

Dans le chapitre 2 nous avons étudié l’application du premier (semis direct) et du deuxième (couvert permanent) principes de l’AC en comparant 3 traitements (semis direct sans mulch, semis direct avec mulch et labour) dans deux provinces du Cameroun : Nord et Extrême Nord. En comparant ces 3 techniques mises en œuvre par des paysans, nous avons pu mettre évidence des différences dans les trois itinéraires techniques concernant la couverture du sol, le nombre d’applications d’herbicide et la quantité d’azote utilisée. Dans l’extrême Nord, il y a également une différence sur la date du premier sarclage. Toujours dans l’extrême Nord, les rendements en coton sont inférieurs de 12 % avec labour, de 24 % en semis direct sans mulch par rapport au semis direct avec mulch. Nous avons cherché l’impact de l’itinéraire technique sur les rendements en coton à l’aide de régressions linéaires. Dans les parcelles labourées, aucune relation significative n’a pu être mise en évidence. Dans les parcelles en semis direct sans mulch, seul le nombre d’applications d’herbicide au semis a pu être relié au rendement. Enfin, pour le traitement semis direct avec mulch, les paramètres significativement liés aux rendements sont la quantité de NPK utilisée, la date de semis et la différence entre les parcelles argileuses et limoneuses. Dans la province du Nord, le rendement ne diffère pas entre les 3 types de gestion du sol. Enfin, la période de floraison a été plus

longue pour le traitement semis direct avec mulch que pour le traitement semis direct dans l'extrême Nord et le Nord : elles sont respectivement de 13 et 9 jours. On constate une différence analogue entre le traitement semis direct avec mulch et traitement labour dans le Nord, la période de floraison étant respectivement de 9 et 8 jours. Le dernier principe de l'AC a été mis en œuvre en installant une plante de couverture dans la céréale, ce qui a permis de doubler la production de biomasse aérienne. Les deux types de traitement comparés pour les céréales étaient la culture conventionnelle (céréales maïs/sorgho) seule et les céréales cultivées en AC, c'est-à-dire associées avec une plante de couverture (*Brachiaria ruziziensis, Crotalaria retusa, Dolichos lablab, Mucuna pruriens,* ou *Vigna unguiculata*). Dans l'extrême Nord, 9.7 t/ha de biomasse ont pu être produites avec du sorgho associé alors que la biomasse était de 4.8 t/ha pour du sorgho seul dans les parcelles conventionnelles. Dans la province du Nord, l'association du maïs avec des plantes de couverture permet de produire 5.2 t/ha de biomasse contre 2.5 t/ha avec le maïs seul. Dans les deux provinces, le rendement en céréales était équivalent ou supérieur pour les céréales associées comparées aux céréales seules. Dans 18 champs de l'extrême Nord, la quantité de mulch de sorgho + *B. ruziziensis* restante après la saison sèche allait de 3 t ha^{-1} à 5 t ha^{-1}. Même si l'AC a montré des avantages à l'échelle parcelle, nos résultats indiquent que des études complémentaires sont nécessaires pour s'assurer de la faisabilité de l'AC à l'échelle exploitation et village.

Le deuxième principe de l'AC (couverture du sol) est étroitement lié au troisième principe (diversification végétale) (Chapitre 3). La couverture du sol dans les champs cultivés en AC dans la région du lac Alaotra à Madagascar peut varier considérablement. Trois systèmes de culture différents ont été étudiés au travers de 91 champs paysans. Les deux premiers systèmes concernaient les parcelles pluviales : (i) maïs + légumineuses volubiles (*Vigna unguiculata* ou *Dolichos lablab*) en année 1, suivi par du riz pluvial en année 2, (ii) le deuxième système de culture incluait plusieurs années de *Stylosanthes guianensis* suivi de riz pluvial; (iii) le troisième système de culture concernait les rizières : en saison des pluies, du riz a été semé suivi de *Vicia villosa* or *D. lablab* en contre saison. La même succession a été répétée chaque année. La biomasse disponible avant le semis s'étalait de 3.6 t ha^{-1} avec *S. guianensis* à 7.3 t ha^{-1} avec *V. villosa*. Nous avons cherché à établir la relation entre la quantité de biomasse au sol et la couverture du sol correspondante pour différentes cultures et plantes de couverture. La relation en quantité de mulch (M) et couverture du sol (C) a été mesurée grâce à des analyses d'images, elle est bien décrire par l'équation $C = 1 - \exp^{(-Am \times M)}$, ou A*m* est le ratio aire/masse avec un $R^2 > 0.99$ dans tous les cas mesurés. Nous avons utilisé cette relation pour explorer la variabilité de couverture du sol observée dans les champs paysans. La couverture moyenne calculée s'étale de 56% pour maïs + *V. unguiculata* à 97% pour maïs + *V. villosa*. Bien sûr, les fonctions agro-écologiques de l'AC s'expriment ou pas en fonction de la quantité de biomasse produite, du mode de gestion des résidus et de la couverture du sol résultante. Pour maintenir 90 % de couverture du sol au semis du riz, la quantité de biomasse de *V. villosa* qui peut être prélevée s'élève à 3 t/ha pour ¾ des champs. Notre étude a montré que dans les conditions paysannes à Madagascar, la production et la conservation de biomasse n'étaient pas toujours suffisantes pour remplir toutes les fonctions agro-écologiques du mulch. De plus, les seuils d'exportation tolérables varient selon les fonctions concernées. Par exemple, une exportation partielle de la biomasse peut ne pas avoir d'impact sur l'efficacité du contrôle de l'érosion, mais peut réduire notablement l'efficacité de contrôle des adventices.

L'équilibre entre les bénéfices potentiels de l'utilisation de la biomasse pour nourrir des animaux dépend des objectifs et contraintes des exploitants. Nous avons donc modélisé les bénéfices potentiels de l'exportation de biomasse des champs à l'échelle de l'exploitation (Chapitre 4). Nous avons effectué nos simulations pour des fermes de tailles différentes. Notre objectif était d'explorer les compromis et synergies entre différents modes de gestion de l'AC (plus ou moins d'exportation de biomasse) et les tailles du troupeau de vaches laitières. Nous avons appliqué des contraintes de couverture minimum du sol (30 à 95%)

à garder dans les champs en AC avant chaque nouvelle saison culturale. Nous avons simulé deux types de marchés du lait : un marché réduit avec un prix réduit du fourrage et un prix élevé du lait et un marché ouvert du lait avec des prix élevés du fourrage et des prix réduits pour le lait. Trois types de fermes ont été modélisées : taille moyenne avec principalement des parcelles pluviales sur colline, taille moyenne avec des rizières et petite taille avec principalement des parcelles pluviales sur colline. Le revenu net total de l'exploitation varie peu quand on fait varier la couverture du sol à conserver et donc la quantité de biomasse exportable. Ce revenu est plus influencé par les caractéristiques du marché du lait. Dans le cas d'un marché limité, il n'est pas profitable pour les paysans d'avoir plus de 7 vaches car les dépenses ne sont pas compensées par la vente des produits animaux. Pour la plupart des situations que nous avons simulées, au delà de 6/7 vaches le modèle choisit d'introduire l'AC pour produire du fourrage sur les collines, mais ceci uniquement si on l'autorise à pratiquer l'AC avec seulement 30 % de couverture du sol. A l'inverse, quand cette contrainte est établie à 95 %, le modèle choisit de ne pas réaliser de l'AC sur les collines. Dans toutes les situations simulées avec le nombre maximum de vaches (12), il a été possible de garder au moins 50 % de couverture du sol sur 80 % des champs de collines. Au final l'AC, peut être profitable pour les éleveurs laitiers grâce au fourrage produit. Le marché du lait et donc la valeur de la biomasse comme fourrage a une influence majeure sur la façon dont l'AC peut être réalisée à l'échelle du champ.

Même avec un nombre réduit de cultures disponibles (28), des milliards de successions différentes sont possibles. Cela nous a conduit à explorer l'étendue des systèmes de culture possibles pour des situations bio-physiques données (chapitre 5). Dans ce chapitre, nous nous sommes intéressés plus particulièrement au troisième principe de l'AC (la diversification végétale). Notre objectif était de proposer une méthode pour la création de systèmes de culture adaptés à différentes situations. Nous avons formalisé les hypothèses mobilisées lors de cette création, elles sont basées sur la caractérisation des champs, le choix d'une plante de couverture adaptée aux situations biophysiques, les combinaisons de plantes en inter-culture et rotation. Ce travail montre que même en ayant appliqué des règles agronomiques ne se basant que sur des critères biophysiques, le nombre de systèmes de culture potentiellement faisables reste élevé. Le nombre de systèmes de culture peut être réduit en prenant en compte les préférences des paysans, leurs objectifs et leurs contraintes. L'évaluation des systèmes de culture *per se,* sans références aux types de ferme, n'est donc pas pertinente. En suivant le même raisonnement et pour chaque type de ferme, le choix des systèmes de culture doit se faire en relation avec d'autres activités (production animale, activités extra-agricoles).

Dans les pays en voie de développement, le principal facteur qui détermine le succès de l'AC est très souvent la compétition pour l'utilisation de la biomasse pour nourrir les animaux. Les bénéfices obtenus en laissant le mulch sur le sol doivent donc en permanence être mis en balance avec les bénéfices potentiels obtenus en utilisant la biomasse comme fourrage. Cet équilibre doit être envisagé à l'échelle de la ferme. La relation entre la quantité de mulch, la couverture du sol et les fonctions agro-écologiques n'a été que partiellement établie dans ces pays. Des recherches complémentaires sont nécessaires pour mieux établir ces relations. La quantification de ces fonctions, des seuils et des relations est nécessaire pour aider à la conception et à la gestion technique de nouveaux systèmes de culture.

Nous appelons également à une description plus rigoureuse des systèmes de culture, des modes de gestion, de la production de biomasse et du mulch quand il s'agit de rapporter des expérimentations concernant l'AC. Cela permettra de donner à la communauté scientifique un meilleur aperçu des impacts et limitations de l'AC pour les petits paysans. Nous espérons ainsi que le débat au sujet de l'adaptation de l'AC pour les pays en voie de développement se fondera davantage sur l'analyse des effets positifs et négatifs de l'AC, et moins sur des positions idéologiques *a priori*.

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Sarah, Lucie and Raphaël suffered from having two parents doing a PhD. At least they have seen that their parents enjoy suffering, which can be a lesson for life. Finally I have to thank Muriel for what we did, what we are and the brilliant future ahead (unless the 21st of December 2012 is really the end of the world…)..

PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (5 ECTS)

- Biomass production, functions of soil cover, threshold and trade-offs around biomass uses; presented at the" Atelier riz pluvial" Antsirabe Madagascar (2009)

Writing of project proposal (3.5 ECTS)

- Direct-seeding Mulch-based cropping system (DMC) design and optimization of farm plans; cases studies in Cameroon and Madagascar (2009)

Post-graduate courses (7.5 ECTS)

- The art of modelling; WUR (2008)
- QUALUS, Quantitative Analysis of Land Use Systems; WUR (2010)

Laboratory training and working visits (3 ECTS)

- Dairy cows nutrition and forage, redaction of a technical manual with a group of Malagasy and French researcher and practitioners; CIRAD Pôle élevage, La Réunion island, France (2007)
- Use of inter specific plant diversification for pest and disease control, laboratory, field visit and scientific meeting; CIRAD La Martinique Island, France (2009)

Invited review of (unpublished) journal manuscript (1 ECTS)

- Crop Protection: CA and weed control (2010)

Deficiency, refresh, brush-up courses (3 ECTS)

- Optimization using GAMS; CIRAD-WUR, Montpellier, France (2007)
- Creation and use of an Access database; CIRAD, Antananarivo, Madagascar (2010)
- Creation and use of an Access database; CIRAD, Montpellier (2011)

Competence strengthening / skills courses (4.5 ECTS)

- Scientific writing and communication; Antananarivo, Madagascar; CIRAD (2006)
- Soil carbon dynamic in CA cropping system, course, laboratory and field investigation; Ponta Grossa University, Brazil (2007)

Discussion groups / local seminars / other scientific meetings (7 ECTS)

- Annual meeting of the "Omega 3 project " of CIRAD; Antsirabe, Madagascar (2010)
- Annual meeting of the "Pepites" project; Antsirabe, Madagascar (2011)
- Annual meeting of the "SCRID" research unit; Antanarivo, Madagascar (2008-2012)

International symposia, workshops and conferences (8.4 ECTS)

- 3rd International congress on conservation agriculture; Naïrobi, Kenya (2005)
- Regional seminar on CA for savanna area; Garoua, Cameroon (2007)
- International symposium on soil and CA; Antananarivo, Madagascar (2008)
- 5th International congress on conservation agriculture; Brisbane, Australia (2011)

Supervision of 8 MSc students (4.5 ECTS)

- Andraiamasinoro, Lalaina Herinaina: biomass production in conservation agriculture cropping system (2009)
- Rakotosolofo, Mirana: biomass production in conservation agriculture cropping system (2009)
- Bruelle, Guillaume: farm modelling (2010)
- Andriamampandry, Ruffin: Biomass production in conservation agriculture cropping systems (2010)
- Niovotiana, Ravaosolo Marie Agnès: Comparison of soil management techniques in controlled experimental fields (2010)
- Van Hulst, Freddy: biomass production in conservation agriculture cropping systems (2011)
- Irintsoa , Laingo: impact of conservation agriculture cropping system on weed control (2011)
- Rakotomalala, Andriamarosata Joël: impact of conservation agriculture cropping system on weed control (2012)

Curriculum vitae

Krishna Naudin was born in 1973 in Paris but grew up in Lozère a rural department in France. After completing his secondary education in 1991 in the local high school of Mende, he decided to follow his passion for biology at Montpellier University. During these years he developed the idea that he would like use his knowledge to the benefit of developing countries. For his first training period he went for the first time to Africa. He worked at the IRD (Institut de Recherche pour le Développement) in Dakar on a key mechanism for ecological intensification of agriculture: biological N_2 fixation. He graduated with a four year university degree “maitrise” in applied plant physiology in 1995. Mindful that knowledge in biological science is not sufficient to have an impact on rural development issues, he decided to pursue three further years of study to expand his expertise. First at the ENSAIA in Nancy (École Nationale Supérieure d'Agronomie et des Industries AlimentairesI) to obtain a fifth year university degree in ”agronomic science” and further at the IRC (Institut des Régions Chaudes) in Montpellier to obtain a master degree in “rural development”. During these years he did his training period first in Montpellier, then in Madagascar and finally he did a master’s thesis in North Vietnam on “alternative cropping systems to slash and burn”. After his graduation in 1999 he spent 15 months in Phnom Penh (Cambodia) working on the other side of rural development: financing. He worked for a funding agency: the AFD (Agence Française de Développement), on rural development project design, evaluation and reporting. Then he was hired by CIRAD and worked in North Cameroon from 2001 to 2005. He worked in a project of the state cotton company (Sodécoton) focusing on soil fertility improvement and farmers’ capacity building. He was in charge of testing the potential of conservation agriculture (CA) to improve cotton and cereal production sustainably. In 2004 Eric Scopel went for a mission in North Cameroon, at this occasion the idea of a PhD on CA cropping design was born. In 2005 Krishna went to Madagascar, the first two years he worked for the NGO TAFA in relation with development project to develop CA cropping systems. Then he worked in a mixed research team between CIRAD, FOFIFA (national agronomic research institute) in Madagascar and Antananarivo University called SCRID working on sustainable rice based cropping system. In 2006 Marco Wopereis, who was then head of the annual crops department of CIRAD, introduced him to Ken Giller who accepted to be his thesis supervisor. The thesis work began at the end of year 2007. Krishna is still in Madagascar up to mid-2013 before he will return to the CIRAD headquarters in Montpellier.

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